Wisconsin Highway Research Program

Minimum Pavement Lift Thickness for Superpave Mixes

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Final Report

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Executive Summary

WisDOT has historically relied on the guideline that the minimum lift thickness of Hot Mix Asphalt (HMA) pavement should be twice as the thickness of the maximum aggregate size used. With the implementation of the new Superpave mix design method in 2000, these guidelines were changed to include pavement lift-thickness values that range between 2.3 and 3.5 the nominal maximum aggregate size used. This meant that traditional designs for overlays of 1.5-2.0 inches thick would be considered "thin lifts," or lifts that would be less than three times the nominal maximum aggregate size. With the use of coarser materials in the HMA design, there is concern that these 'thin lifts' could be problematic during compaction in the field. To address this problem, WisDOT determined that research and possibly new guidelines were needed for the thickness to nominal maximum aggregate ratio in order to achieve an optimal lift thickness for compaction of Superpave mixtures.

The objectives of this study included: quantifying the effects of varying the lift thickness on the compaction and performance of selected types of Asphalt pavement mixtures used commonly in Wisconsin. The findings form the study, which would include laboratory and filed experiments, would then be used to establish revised guidelines for minimum lift thickness for Superpave mixtures to be used in construction. Efforts to develop these guidelines included consideration of data generated from construction projects using Superpave mixes placed during the 2000 and 2001 paving seasons.

This research project included four main tasks: a literature review of publications, journals and articles specific to Superpave mix designs and testing using the Superpave

methods; a survey of contractors and state highway agency experiences with lift thicknesses using the new method; a laboratory analysis of mix design applications and; a related field study.

The literature review included analysis of the laboratory compaction and testing methods using Superpave mix designs, field compaction studies, as well as studies of techniques and difficulties reported in compacting asphalt mixtures related to lift thickness. The survey of contractors and State Departments of Transportation enabled the research team to document the state-of-the-practice and collect information about experiences of practitioners regarding relationships between lift thickness and compaction results. Searching WisDOT's construction databases also provided information on HMA construction in Wisconsin as it relates to lift thickness.

The laboratory research included testing and analysis of compacting two types of mixes in the Superpave Gyratory Compactor using the Gyratory Load Plate Assembly (GLPA): (1) mixes batched and mixed in the laboratory, and (2) loose mixes sampled from field projects. The GLPA was used to model how thickness affects the energy required throughout the compaction process. Volumetric analysis of the data was also performed. The samples were extracted to test the mixes for the degradation of the aggregates during the compaction process.

The field research included compaction of various lift thicknesses at sites selected for the variety of diverse aggregates. Specific construction projects were chosen to look at the effect of materials, bases and gradations on the density achieved during compaction. The aggregates were compacted at several lift thicknesses. Testing included lift thicknesses that were thinner than the current recommendations, several at the current state specifications, and several with lifts greater than current recommendations. Nuclear density meters/gauges were used to measure the density of each lift.

Upon completion of the literature review and survey results from the various state highway agencies, the data from the laboratory and field studies was compiled and analyzed to identify trends and patterns.

Contractors surveyed varied in their responses as to what the minimum pavement thickness should be and ranged between 1.75 and 4 times the nominal maximum aggregate size. The survey of the Midwestern DOT's indicated a much smaller range of responses; with most stating that a range of 3 to 4 times the nominal maximum aggregate size was best. Searches of the WisDOT construction databases revealed no major problems in achieving density in the field that could be definitively related to lift thickness.

The results of the laboratory study indicated that sample size (sample thickness) has an important effect on achieving required density using the Superpave Gyratory Compactor (SGC). A ratio of sample thickness to maximum aggregate size in the range of 4-6 is required to ensure that sample thickness will not interfere with achieving density. The results also indicated that the minimum ratio required is somewhat affected by aggregate source and gradation.

The field study results did not agree with the laboratory results. No significant trend between density in the field and lift thickness could be defined. It was therefore concluded that field result do not offer any evidence that lift thickness below the ratio of 3.0 require more compaction effort (roller passes or heavier rollers) to achieve density. There are a number of factors that could have affect the field study such as the types of mixtures used, the sources of aggregates, and the shape of aggregates. It is therefore recommended that more projects be studied with higher-grade mixtures (E10 and E30) and/or more angular aggregates to confirm the field findings before any changes in guidelines are made. In addition, a more elaborate study in the laboratory is needed to explain the significant effect of sample size on density measured in the Superpave Gyratory Compactor.

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

The Wisconsin Department of Transportation (WisDOT) has traditionally specified 75mm dense graded overlays for pavement rehabilitation projects. These overlays are commonly placed in two layers: a 44mm binder layer and a 31mm surface layer. It is a well-recognized fact that the effectiveness of compaction is related to the ratio of the nominal maximum aggregate size to total lift thickness. Historically, these layer thicknesses have been based on the rule-of-thumb that lift thickness should be twice the nominal maximum aggregate size.

In 2000, WisDOT implemented the volumetric Superpave mix design procedure. This change was based on research efforts conducted by the Strategic Highway Research Program in the early 1990's. Through the use of different gradation procedure bands and aggregates with more controlled properties, the change to Superpave mix design is intended to provide Wisconsin residents with better performing, longer lasting roads.

While the use of this mix design method has provided higher quality mixes, it has also created some difficulties for the contractors building Wisconsin's highways. Contractors had many years of experience with the Marshall-mix design method previously used in Wisconsin. This experience enabled them to manage any compaction difficulties that might arise when working with these types of mixes. In most cases, this experience could be applied to the application of the new mix design method, however, some of that ability to manage compaction in the field was lost with implementation of the new design methodology.

Superpave mixture design criteria include two important requirements: 1) selecting a PG grade, and 2) using fine aggregates with certain levels of angularity. Although there are several other requirements, these are relatively new and their effect on mixture design and performance are not fully understood. The effect of changing one PG grade on the relative performance of asphalt mixtures during construction and during pavement life is unknown. The effect of the level of sand angularity is also unknown. Both factors can and oftentimes do interact to affect mixture performance.

One example of the challenges resulting from this shift in methodology involves the use of coarser materials, especially on roads with higher traffic volumes. Coarser mixtures tend to be more difficult to compact. Rolling patterns and, in some cases, the roller types previously used for the Marshall-mix design method were insufficient to achieve the desired density under the Superpave mix design method. As a result, new methods and techniques had to be implemented, such as looking at the potential for laying the material in thicker lifts than was required by the Marshall-mix method. In addition, contractors considered using heavier rollers, changing roller patterns or the number of roller passes to address this issue.

1.2 PROBLEM STATEMENT

WisDOT has historically relied on the guideline that the minimum lift thickness of Hot Mix Asphalt (HMA) pavement should be twice as the thickness of the maximum aggregate size used. With the implementation of the new Superpave mix design method in 2000; these guidelines were changed to include lift-thickness ratios that range between 2.3 and 3.5 the nominal maximum aggregate size used. This meant that traditional designs for overlays of 1.5-2.0 inches thick would be considered “thin lifts,” or lifts that would be less than three times the nominal maximum aggregate size. With the use of coarser materials in the HMA design, there is concern that these ‘thin lifts’ could be problematic during compaction in the field. To address this, WisDOT determined that new guidelines were needed for the nominal maximum aggregate size to thickness ratio in order to achieve an optimal lift thickness for compaction of Superpave mixtures.

1.3 RESEARCH OBJECTIVES

The objectives of this study included: quantifying the effects of varying the lift thickness on the compaction and performance of Hot Asphalt Mix pavement mixtures in Wisconsin. The study will be done in the laboratory by changing sample size in the gyratory compactor and in the field by varying pavement lift thickness during compaction. The findings from the study would then be used to establish guidelines for the minimum pavement lift thickness for Superpave mixtures produced using different aggregate sources and nominal maximum aggregate size. The overall goal for the development of these guidelines is to establish reasonable standards for using Wisconsin materials that allow contractors to achieve standard mixture density requirements in the field.

1.4 RESEARCH METHODOLOGY

This research project included four main tasks: a literature review of publications, journals and articles specific to Superpave mix designs and testing using the Superpave methods; a survey of contractors and state highway agency experiences with lift thicknesses using the new method; a laboratory analysis of mix design applications and; a related field study.

The literature review included analysis of the laboratory compaction and testing methods using Superpave mix designs, field compaction studies, as well as studies of techniques and difficulties reported in compacting asphalt mixtures related to lift thickness.

The survey of contractors and State Departments of Transportation enabled the research team to document the state-of-the-practice and collect information about experiences of practitioners regarding relationships between lift thickness and compaction results. Searching WisDOT's construction databases also provided information on HMA construction in Wisconsin as it relates to lift thickness.

The laboratory research included testing and analysis of compacting two types of mixes in the Superpave Gyratory Compactor using the Gyratory Load Plate Assembly (GLPA): (1) mixes batched and mixed in the laboratory, and (2) loose mixes sampled from field projects. The GLPA was used to model how thickness affects the compaction process. Volumetric analysis of the data was also performed. The samples were extracted to test the mixes for the degradation of the aggregates during the compaction process.

The field research included compaction of various lift thicknesses at sites selected for the variety of diverse aggregates. Specific construction projects were chosen to look at the effect of materials, bases and gradations on the density achieved during compaction. The aggregates were compacted at several lift thicknesses. Testing included lift thicknesses that were thinner than the current recommendations, several at the current state specifications, and several with lifts greater than current recommendations. Nuclear density meters/gauges were used to measure the density of each lift.

Upon completion of the literature review and survey results from the various state highway agencies, the data from the laboratory and field studies was compiled and analyzed to identify trends and patterns.

SUMMARY

In the laboratory, sample size (sample thickness) has an important effect on achieving required density using the Superpave Gyratory Compactor (SGC). A ratio of sample thickness to maximum aggregate size in the range of 4-6 is required to ensure that sample thickness will not interfere with achieving density. The results also indicated that the minimum ratio required is somewhat affected by aggregate source and gradation.

The field study results, however, could not be used to confirm the findings from the laboratory study. There was no evidence that lift thicknesses below the ratio of 3.0 require more compaction to achieve density. There are a number of factors that could be involved in the discrepancy between laboratory and field.

The following chapters provide a detailed discussion of the research that was conducted to analyze the Superpave mix design needs for Wisconsin. Chapter one provides an introduction to the study and background information important to the development and analysis of the research results. Chapter 2 summarizes the results of the literature review. A summary of the contractor and State DOT survey results is provided in Chapter 3, along with the information gathered from WisDOT's database. Chapter 4 describes the laboratory testing method and results, including testing of the mixes from the laboratory and those gathered in the field. The organization, methodology and results of the field study are discussed in Chapter 5. Chapter 6 provides a comparative analysis of the field and laboratory results, in addition to a discussion of the difficulties experienced during this study, along with recommendations for future research needs. References and Appendices are appended to the end of the report.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

The areas considered under this study are broad. They include researching the variations in gyratory compaction methods and techniques, as well as other various laboratory tests required by the Superpave Mix Test Method, In addition, this study required a review of the effects of various rollers and techniques on compaction of mixes in the field. In order for a study of this nature to be valid, a literature review of each area was conducted. In order to conduct a comprehensive laboratory analysis, literature of asphalt testing techniques and methods was reviewed, along with current information on gyratory compaction. New techniques used to study laboratory compacted mixes were also reviewed for applicable methods of analysis and comparison.

A literature review of comparable field studies that included related compaction processes were also conducted to gain a better understanding of the aspects involved in field compaction. In addition, literature searches were conducted to garner an understanding of new technologies and their application to the construction process.

2.2 LABORATORY METHODOLOGY

During the laboratory study, Superpave samples were batched, mixed and compacted according to approved techniques and methods by the WisDOT. Several resources were used to ensure that the approved techniques and methods were applied. Among these were National Asphalt Paving Association's <u>HMA Materials, Design, & Construction</u> book, which describes the basics of Superpave mix design. This book includes descriptions of the variety of aggregate tests, such as the soundness and wear tests, and fine aggregate angularity tests, that must be used to design appropriate mixtures. It also describes the proper procedures required for each mix method and test, such as the amount of mixing and curing time for HMA, and the compaction setup. In addition, it provides the target value tables for Voids in Mineral Aggregate (VMA), Voids Filled with Asphalt (VFA), and the number of gyrations (Roberts. 1996). While this book provided valuable information, it was published in 1996, and as a result, some of the information was outdated and in need of revision.

A presentation by the Federal Highway Administration (FHWA) in the Fall of 2001 provided a useful review of the methodology to complete a Level 1 Superpave Mix Design, as did Materials for Civil Engineering and Construction Engineers (Mamlouk et al. 1999).

WisDOT's Highway Technician Certification Program also provided information on the steps needed to perform the various tests on each mixture, including specific gravity tests and related extractions (Lundin. 1999).

Related AASHTO procedures were examined for information related to mixing and compacting samples; testing the mixtures for bulk and maximum specific gravities; and performing extraction testing on compacted asphalt mixtures (AASHTO. 1995).

Strategic Highway Research Program reports provided explanations for the use of the SGC and its setup (Comisky et al. 1994). All of these basic HMA resources were used to design the testing procedures conducted during the laboratory phase of the study.

One of the recent changes to mix design procedures reflects the finding that climactic temperature is not a factor in determining the number of gyrations used to compact an asphalt mixture. Under the new method, only the level of traffic is considered (Hansen 1999). Also, new information indicated that the restricted zone is no longer necessary, as Superpave mixes have gradation properties controlled such that going through the restricted zone does not weaken the pavement structure (Kandall & Cooley 2001).

WisDOT provided many resources related to the testing and evaluation of bituminous materials. The 1996 Standard Specifications and its Supplemental Specification from 2000 provided information relative to WisDOT's gradation bands and the required test values that a HMA must meet to be approved. The specifications also include the comparison value ranges for extractions and specific gravity testing. This information allowed the research team to compare two tests to check for correlation and agreement (WisDOT 1996 and 2000).

As no fine blends were available from Source L, the above information assisted in designing the needed fine blend. This information was also used in testing all of other mixtures as well. By using current local contractor and WisDOT techniques a comparison of the results of this study can be made with those of any agency.

2.3 SUPERPAVE GYRATORY COMPACTOR STUDIES

2.3.1 Gyratory Load Plate Assembly (GLPA)

The Gyratory Load Plate Assembly (GLPA) developed at the University of Wisconsin – Madison (Figure 2.1) is one of the best ways to analyze the affects of sample thickness on compacted samples. The GLPA includes three load cells offset by 120° on a plate that can be put in the mold. During the compaction insight is gained into the forces that are being applied to the mixture by measuring the forces on the three loadcells (Guler et al. 2000).

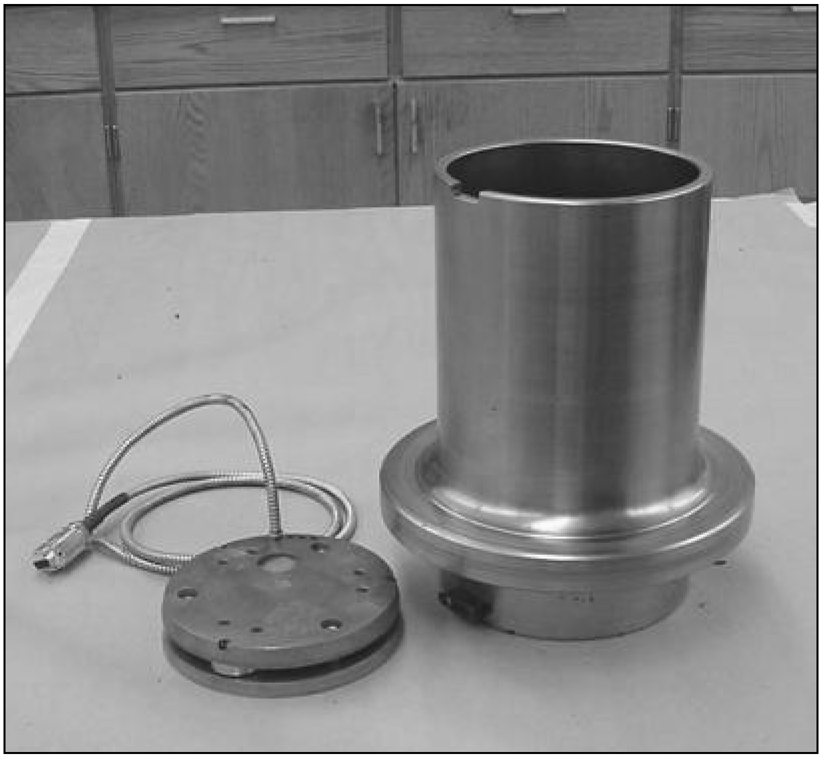


Figure 2.1. Gyratory Load Plate Assembly and SGC Mold

The resistance of the mix to the compactive effort that is being applied to the sample is measured as a means of determining how difficult a mix is to compact. This is shown in equation 2.1 (Delage. 2000).

$$\omega = 4*e*P*\theta/(A*h) \qquad (2.1)$$

Where: ω = resistive effort
e = eccentricity of the resultant
P = magnitude of the resultant
θ = angle of gyration (1.25°)
A = area of cylinder
h = height of specimen at any given gyration

This modeling can be used to develop the Construction Friction Index (CFI) and the Traffic Friction Index (TFI) as shown in Figure 2.2. The CFI represents the frictional resistance to compaction up until 92% G_{mm}; the density that would be achieved during the construction of the pavement by roller compaction and the paver screed. The TFI is the resistance to compaction in the range of 92% to 98% G_{mm}; the area that would be achieved by traffic densification and represent the pavement's longevity. Both are modeled under the work curve generated from the GLPA (Delage 2000).

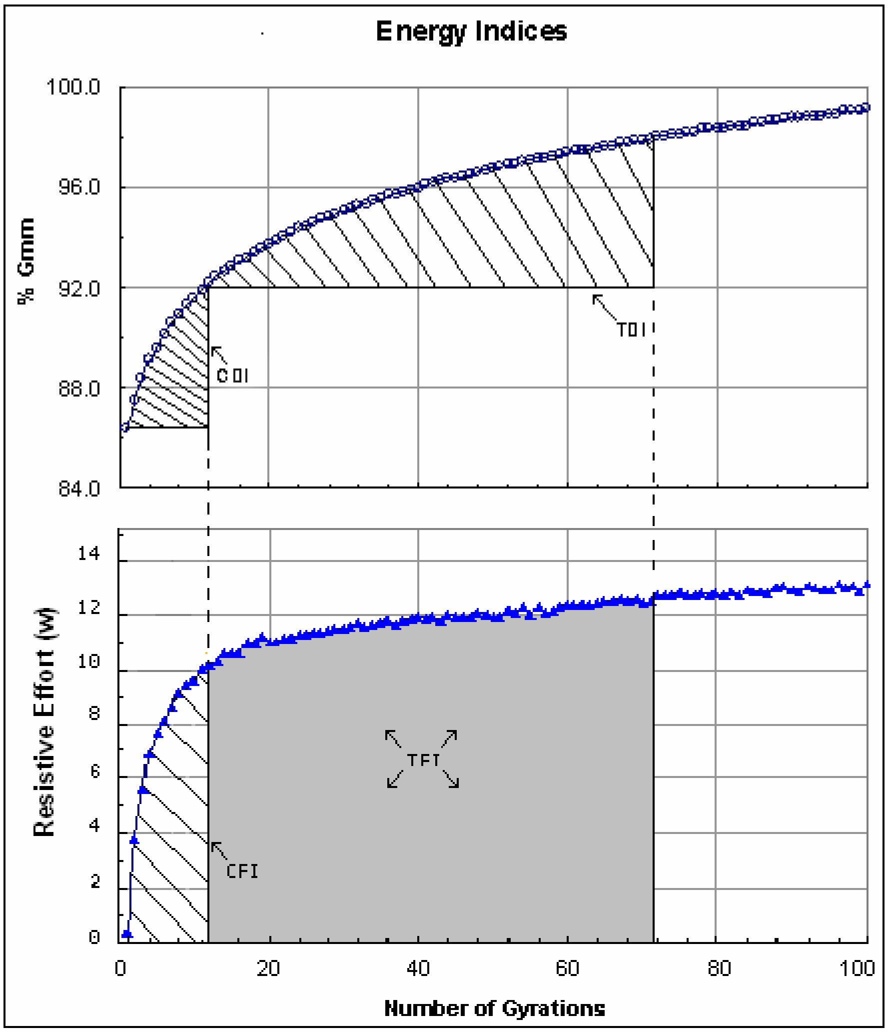


Figure 2.2. Energy Indices

Another modeling approach way uses the Construction Energy Index (CEI) and the Traffic Energy Index (TEI), also shown in Figure 2.2. The CEI and TEI are modeled by looking at the various areas under the densification curve developed during gyratory compaction. The CEI represents the area of compaction that occurs when the mix is compacted from the $N_{initial}$ gyration to 92% G_{mm}, or the construction compaction area. TEI is represented as the area under the densification curve from 92% G_{mm} to 98% G_{mm}. This is the area that would be densified by traffic or additional densification achieved by the compaction effort of the paving crew (Bahia et al.1998).

An estimate of how much compactive effort is necessary for compaction can be obtained by comparing the different construction indices (CEI and CFI). By comparing the results of different mixes, an estimate of how difficult a certain mix would be to compact can be determined. This comparison may also reveal whether thickness has an effect on the compactive effort required in the SGC.

2.3.2 Thickness and Compaction Modeling Studies

A 1997 study by Hall, Dandu and Gowda provided a great deal of information on how to set up the laboratory phase of a thickness and compaction. In this study, samples sizes ranging from 2,000 to 6,500 grams were compacted. The results of this study showed that sample sizes less than 3,500 grams had higher air void contents than the larger sample sizes. This was true for coarse, medium and fine gradations and modified asphalts. It was generally observed that sample sizes of 3,500, 5,000, and 6,500 grams achieved the same amount of compaction inside the SGC. Samples at 2,000 grams were generally 2% to 3% less dense than the larger sized samples. It was also found that the difference in density between different sample sizes decreased with increasing asphalt content (Hall et al. 1997).

A study from Sweden also found that a 20% reduction in sample height had an effect on the density achieved during compaction. Conducted by Jonsson, this study also used a compaction work model (equation 2.2), developed by Kezdi, similar to the one used at the University of Wisconsin (Jonsson and Kezdi. 1969).

$$\rho(S) = \rho_\infty - (\rho_\infty - \rho_0) * e^{\wedge} -(S/C) \tag{2.2}$$

where: $\rho(S)$ = current density as a function of work (g/cm^3)
S = compaction work (N*m)
ρ_∞ = calculated maximum density
ρ_0= initial density
C = compaction resistance (N*m)

Jonsson's study also looked at vibration along with compaction in the laboratory, which was not considered as part of the current study.

2.4 COMPACTION STUDIES

2.4.1 Compaction Methods and Background

Compaction has been described by many as the key to a good pavement. Proper compaction of even a poor mix can increase a road's durability, strength longevity and performance (Hughes et al. 1989). Good compaction can prevent raveling and increase mechanical stability (reduce rutting and shoving potential) (Linden et al. 1987).

In order to analyze the compaction methods, it is important to understand what equipment was selected and how it was used in the compaction process. The key pieces of equipment that are used include: (1) the paver and its screed, (2) static steel rollers, (3) pneumatic tire rollers; and (4) vibratory rollers.

The screed is the part of the paver that provides the initial compaction of the HMA. The screed takes the mix from the augers and paver, and compacts it to about 70% to 80% of the theoretical maximum density. It attacks the mix at an angle; being thicker on the paver side, then sloping downward to the back of the screed. The main action of the screed that provides densification is the vibration. The vibration is controlled to correspond to the mat thickness, with a lower amplitude vibration used for thinner lifts and higher amplitudes for thicker lifts (Warren 1993). The screed and paver are the initial controls on the quality of the pavement. The forces that the screed applies to the mix can vary depending on the speed of the paver, uniformity of material being fed through the paver, and thickness of the mat being laid (Hughes et al. 1989). The reason for these differing forces is that the screed floats on the mix, and attacks the mix at an angle, thus resulting in downward and forward forces on the mix that are applied in differing manners (Linden, et al, 1987).

Rollers compact the HMA by applying downward forces on the mix from the weight of the roller through its area of contact. The forward and backward movement of the rollers also applies a horizontal load to the mat. Each of the rollers applies this loading in different ways that need to be reviewed separately.

Static steel wheel rollers were the first type used on HMA's, beginning in 1875 (Hughes and Tunicliff. 1989). With a large diameter and a small area of contact, the static steel rollers can put a large amount of force on the material to increase the density of the HMA. The amount of the contact area varies with changes in the speed of the roller and the density of the mat. As the mat is fresh and warm, the roller will "sink" into the mat, increasing the contact area and decreasing the amount of force per unit area. The amount of this force per unit area increases as the mat densifies, resulting in less sinking of the roller "sinks" into the mat. The downward force used for static compaction of mixes comes from the weight of the roller, which can vary from 3 to 14 tons. Static rollers can be used in the initial "break-down" position behind the screed, knocking the air out of the mat and achieving the initial increase in density. It can also be used as the final "cold roller", smoothing out the pavement surface with minimal increase in density (Warren 1993).

The same principles are true in the case of the pneumatic tire roller, but more forces are involved in the process. Instead of one line of contact with the static drum rollers, tire rollers use anywhere from 7 to 9 tires on an axis to apply the loading to the pavement. The vertical pressures applied by the tire rollers are a component of the tire pressure, load of the machine, and tire design. The spaces between the loading areas of the tires result in a kneading action to the surface of the mat, which some say may or may not be more productive than the steel rollers (Geller 1982). Again, speed of paver operation and the density of the mat are factors in the pressure applied to the mat. Pneumatic tire compactors are used in the breakdown position, or as the second roller in a three-roller combination, in charge of achieving the target density (Warren, 1993).

The third type of roller used to compact HMA is the vibratory roller. The vibratory roller is essentially a static roller with one important modification; an eccentric weight rotates inside the drum(s) causing a dynamic, or impact, compactive force in the mixture (Kennedy and Jonsson. 1984). The dynamic force applied is proportional to the mass of the eccentric weight, eccentric radius, and the frequency of rotation. The amplitude is a function of the mass of the eccentric weight, eccentric radius, and the vibrating mass (Jonsson 2001). For optimal compaction, vibratory impacts should be spaced around ten to twelve impacts per foot. The efficiency of the vibratory compactor is achieved with proper impact spacing and amplitude (Warren 1993). The operator of the vibratory roller has to be careful, as he/she is responsible for the dynamic action, which can be detrimental if improperly applied (Geller 1982). For thinner lifts, the highest frequency and the lowest amplitude should be used to achieve optimal compaction (Hughes et al. 1989). Some publications suggest that thinner lifts should not receive vibratory compaction (Kennedy et al. 1984). Others state that vibratory compaction of thin lifts is acceptable (Alexander 1982).

Contractor experience often dictates which rollers are used and what pattern the operators should follow. The sooner the rollers are on the mat behind the paver, the better. Experience indicates that once the mat cools below 80° C., it is extremely difficult to achieve compaction. The desired density should be reached before this point, but the viscosity-temperature profile should be used to determine the optimum window for compaction (Warren 1993).

Within the mat, the stiffness increases during compaction due to the increased inter-particle reaction and the increasing viscosity of the asphalt. The mix used is also a factor to consider when looking at the inter-particle friction. The type of gradation (fine, coarse, etc.), particle shape and surface texture are all influences in a mixture's resistance to compaction. Uniform dense-graded mixtures tend to be easier to compact than coarse or gap-graded mixtures, but overly fine mixtures can also be difficult to compact (Scherocman 1987). The amount and type of filler in a mixture may also affect a mixture's resistance to compaction (Tunnicliff et al. 1974). The amount of asphalt is also an influence on the densification process, as too little asphalt can keep a mixture from achieving the target density (Hughes et al. 1989).

This review of the compaction process, not only provided useful background information, but also enabled the research team to gain an understanding of the state-of-the-practice procedures currently used. This information translated into training preparation for the field technicians regarding expected outcomes and procedures at the various construction sites.

Thickness Related Documentation

While much of the asphalt research relates to the Marshall or Hveem mix design methods, it offered important relative to thinking and reasoning process that go into many of the previous and current thickness recommendations being used. The lift thickness is often specified as a ratio of the lift thickness divided by the mixture's nominal maximum aggregate size. In most publications, it is stated that the lift thickness should be at least twice the nominal maximum aggregate size (one sieve size larger than the first sieve to retain more than 10 percent) (Hughes, Epps, Scherocman et al. 1989). Other publications recommend a thickness of three to four times the nominal maximum aggregate size (Jonsson). Current use of the Superpave mix method has spurred discussions of establishing the three to four times the nominal maximum aggregate size as the standard (World Highways 2001). The State of Wisconsin has changed the minimum thickness from two times the nominal maximum aggregate size to the values shown in Table 2.1 (WisDOT 2000).

Table 2.1. WisDOT Lift Thickness Specifications

Nominal Size (in Inches (mm))	Minimum Layer Thickness (in Inches (mm))	Ratio (Thickness/Nominal Size)
1.5 (37.5)	3.5 (89)	2.33
1.0 (25.0)	3.25 (83)	3.25
0.75 (19.0)	2.25 (57)	3
0.5 (12.5)	1.75 (44)	3.5
0.375 (9.5)	1.5 (38)	4

Most agree that Superpave mixes are more difficult to compact than the Marshall mixes were. As part of the SPS-9 projects contracted by the Strategic Highway Research Program (SHRP), seven Superpave test projects were compacted in 1992 and 1993. The test sections had Superpave HMA placed in lifts as thin as 1.25" for the surface lift. None of the projects reported any difficulties in compaction. Some even commented that the Superpave mixes were easier to compact than the normal state mixes (Johnson et al. 1995).

Another discussion between the Minnesota Department of Transportation (MnDOT) and the Asphalt Institute related some of the difficulties that Minnesota was facing in achieving density with Superpave mixes. The difficulties noted by MnDOT included compacting 9.5mm mixes, compacting mixes that consisted of 100% limestone, and compacting mixes over concrete. Most of the comments indicated that the problem was a lack of experience and education, and that the contractors needed to deal with compaction of Superpave mixes on a daily basis, instead of a project wide basis (Palmer 1999).

2.4.2 Other Relevant Research

Another important aspect of this study is the nuclear density testing. In order to determine how dense the different lifts in the field were, the nuclear density machine was used. Asphalt coring could have been used, but that would have been a time-consuming approach yielding fewer samples. The nuclear density machine is an accepted method of testing for pavement density. A study by Schmitt et al in 1997 provided guidance for conducting the field research phase of this project. Their study compared coring to nuclear density methods. Test sections varying from 500 to 10,000 feet in length were used. The results of the study also documented that a 1 to 4 minute test yielded the best results. Their statistical analysis indicated that nuclear density machines could be very accurate devices, but that location in the mat width had to be taken into consideration. It also provided some useful statistical analysis tools for analysis of the nuclear density results (Schmitt 1997).

2.5 CONCLUSION

After gathering and reviewing literature and data on laboratory testing methods of HMA, Superpave gyratory compaction, field compaction studies, and nuclear density testing, the next step was to check with other agencies for there input on the research topic. The State of Wisconsin, the contractors of Wisconsin and other midwestern states were surveyed regarding their use of Superpave asphalt mixes and their respective concerns and problems.

CHAPTER THREE

SURVEY RESULTS

3.1 MIDWEST SURVEY RESULTS

In order to gather recent information about requirements implemented by different state highway agencies for compaction of Superpave mixtures, a survey questionnaire was sent to twelve midwestern state highway agencies. The survey questionnaire provided in Appendix A, focused on thickness-related issues pertaining to Superpave mixes; specifically the lift thickness and any difficulties in achieving density.

Indiana

Indiana has noticed some tenderness problems with some of their mixes on warm days. Their specification is based on the maximum aggregate size, instead of the nominal maximum aggregate size. Their 2000 specification was between 1.5 to 3 times the maximum aggregate size. In 2001, this specification shifted to 2 to 4 times the maximum aggregate size.

Iowa

Iowa has encouraged contractors to use low amplitude, high frequency vibratory compaction during the breakdown process to assist in the densification of Superpave mixtures. The minimum lift thickness to nominal maximum aggregate size used is typically a ratio of 3, with the surface lift being no thicker than 2 inches.

Kentucky

Thin surface lifts of 1 to 1.5 inches have proved to be problematic in Kentucky. Vigorous vibratory compaction of these thin surface lifts has led to diminished smoothness.

Kentucky generally uses a minimum ratio of lift thickness to nominal maximum aggregate size of 3 to 4 in their mix designs.

Minnesota

Minnesota has documented a few cases of tender mixes preventing the contractor from achieving the target density. Generally, MnDOT recommends a ratio lift thickness to nominal maximum aggregate size of 4 for its Superpave mixtures.

Missouri

Prior to 2000, Missouri contractors had difficulty in achieving compaction with their Superpave mixtures. In order to combat those problems, many contractors obtained Pneumatic tire rollers weighing 20 tons or greater, facilitating compaction. MoDOT generally recommends a ratio of lift thickness to nominal maximum aggregate size of 3.

Nebraska

Contractors in Nebraska initially had problems in achieving density with Superpave mixtures. Attention to roller patterns, roller sizes and the type of rollers being used improved their ability to achieve targeted density. Nebraska also uses the ratio of lift thickness to nominal maximum aggregate size in the range of 3 to 4.

North Dakota

North Dakota DOT has not reported any problems with Superpave mixtures. They have no minimum lift thickness limits on there Superpave mixtures.

South Dakota

South Dakota DOT has not witnessed any more difficulties with their Superpave mixes than what they have seen with their high volume mixes. Their minimum specification for lift thickness ranges from 4 to 5.

Table 3.1 provides a summary of the responses received from each state agency. As described in the table, state agencies vary significantly in their requirements for minimum lift thickness. The breadth of ranges includes thicknesses as low as 2x the maximum size to as high as 5x the nominal maximum size; with the most common minimum lift thickness ratio in the range of 3 to 4. This matches what Wisconsin recommends for its pavements. The most commonly reported problem reported related to increasing difficulty in compacting Superpave mixes, with a few states recommending heavier equipment and more vigorous compaction procedures.

Table 3.1. Summary of Survey Results

State	Lift Thickness Range (x Nom Max Size)
Indiana	2 to 4 x
Iowa	3 x
Kentucky	3 x
Minnesota	4 x
Missouri	3 to 4x
Nebraska	3 to 4x
North Dakota	---
South Dakota	4 to 5x
Wisconsin	3 to 5x

3.2 WISCONSIN CONTRACTOR'S SURVEY

A second effort included an effort to document local practices. To do this, a survey questionnaire was sent to Wisconsin asphalt contractors by the Wisconsin Asphalt Paving Association (WAPA) in the spring of 2001. The survey questionnaire is included in this report as Appendix A. The questionnaire was designed to gather data on the types of experiences contractors had had with Superpave mixtures. The focus of the survey included questions related to problems experienced with Superpave mixtures, whether certain types of mixtures tended to be more difficult to work with than others, and their recommended minimum lift thickness for pavements. 30 people were contacted, representing 22 asphalt paving companies. 12 responses from 10 companies were received. The companies that did not respond by the target date were contacted again to submit a response. No responses were received from the follow up. The results of the survey are provided in Table 3.2.

Table 3.2. Wisconsin Contractor Survey Responses

Response	Recommended Ratio or Thickness	Problems/Comments
1	2.5x	More manufactured sand, more difficult to compact
2	---	No comments reported
3	1.75x	No comments reported
4	2.5"	Sometimes having problems with poor bases. Thicker lifts are easier
5	---	Difficulty achieving state targeted density
6	---	Thicker is better
7	2"+	The cooler the mix, the easier it is to get density (100-120°F)
8	3x	Problems with crushed aggregate bases.
9	3.5x	Thin mats proved to be difficult, thicker is better.
10	2"	Thin lifts.
11	1.5"	More compaction required for thinner coarse lifts.
12	4x	Difficulty with High Fracture/Low Asphalt E10 mixes, or Fine Aggregate Angularities above 45

The results of the survey demonstrate very diverse opinions. The minimum lift thickness recommended by the contractor respondents ranged from as thin as 1.5 inches and 2.5 times the nominal maximum aggregate size up to 2.5 inches and 4 times the nominal maximum aggregate size. The average response range was approximately 3 times the nominal maximum aggregate size.

The problems observed by the respondents in achieving density ranged from issues related to bases, to difficulties with the fine aggregate angularity or amount of sand in the mixture. The most common response (5 of 12 respondents) was that thin layers were more difficult to compact or that thicker layers were easier to compact. This aligns with the findings of the literature review relative to Superpave mix compaction.

3.3 WISCONSIN DOT DATABASE INFORMATION

WisDOT's databases were also accessed for projects that using Superpave mixes that did not achieve the target density or had problems with the Quality Assurance (QA) results. QA results were checked for the 2000 paving season and the 2001 results were checked through the end of July. Density results were also compiled for the 2000 and 2001 paving seasons through July of 2001.

945 quality assurance verifications were scanned for non-satisfactory results. The 945 results represent 7 to 10 percent of the total number of test results conducted on asphalt concrete mixtures. 23 of the 945 HMA quality assurance results, or 2.4% of the results reviewed reported problems.

Density testing from those same two years resulted in a database of 123 results. 12 of the 123 reports, or 9.8%, included unsatisfactory results. Of these twelve tests, only two were actually due to low-density readings (1.7% of the total tests). The remaining non-satisfactory tests were the result of too much variation between gauges, bad gauges, or improper test methods. None of the non-satisfactory nuclear density test results correlated with the non-satisfactory quality assurance results.

CHAPTER FOUR

LABORATORY STUDY: EXPERIMENTAL SETUP, DESIGN AND ANALYSIS

In this chapter, a description of each phase of the laboratory study is provided. First, an explanation of the experimental setup will be covered. The next, a discussion of the initial laboratory results, along with the analysis follow. The results from the field mixes compacted in the laboratory are provided included in this section following the initial laboratory mixes. All of the information was compared in order to derive the conclusions of the laboratory study.

4.1 EXPERIMENTAL SETUP

Four mix designs were initially tested in the laboratory to determine the typical densification and shear resistance patterns, as well as the trends to be measured during the course of the study. Based on these results, the materials from four field studies were added to the experimental work. The materials from the four field studies accounted for seven different mix designs, resulting in a total of eleven different mix designs tested in the laboratory study.

Table 4.1. Experimental Setup

	Material Type	Crushed Stone				Coarse Gravel			
	Gradation Type	Coarse		Fine		Coarse		Fine	
	Nom. Max. Size	19mm	12.5mm	19mm	12.5mm	19mm	12.5mm	19mm	12.5mm
Source	K							X	X
	L	X	X	X	X				
	M	X			X				
	N			X					
	P			X	X				

X – Denotes type of mix studied in the laboratory

Table 4.1 shows a breakdown of the experimental setup. As can be observed, the mixes used during the laboratory phase included various combinations of sources, gradations, aggregate types, and nominal maximum aggregate sizes. All of the crushed stone mixtures tested were from crushed limestone sources, except for source M, which came from a crushed granite source.

Table 4.2. 12.5mm Mix Design Properties

	Source				
	LC	**LF**	**K**	**M**	**P**
Sieve (mm)	**Gradation (% Passing)**				
25	100	100	100	100	100
19	100	100	100	100	100
12.5	95.2	97.6	97.3	91.9	98.3
9.5	74.8	87.7	89.4	76.4	90.4
4.75	46.9	72.8	66.3	63.9	67.4
2.36	28.4	54.9	55.2	45.8	49.7
1.18	17.5	40.7	44.2	29.4	36.7
0.6	10.8	28	30.5	18.9	24.1
0.3	6	13.2	14.2	10.5	10.7
0.15	4	6.9	6.9	5	6.1
0.075	3.2	5.2	4.6	3.2	4.8
Volumetric Properties					
%AC	5.3	6.1	5.3	5.5	5.8
VMA	14.9	17	15	15.9	15.3
VFA	73.2	76.1	73.3	74.9	73.9
Dust/Binder	0.8	0.9	1.1	0.6	1.1
FAA	46.1	42.1	42	47	43.1
Gmm @ N_{init}	84.9	88.3	88.4	88.1	88.5
Gmm @ N_{des}	96	96	96	95.3	96
PG Grade	64-22	58-28	58-28	58-28	58-28

Table 4.2 shows the gradations and the volumetric properties of the different 12.5 mixes used in the study. The volumetric properties cover the percentage of asphalt (%AC) used, and it's type in the PG Grade. It also displays the Voids in Mineral Aggregate (VMA),

Voids Filled with Asphalt (VFA), the dust to binder ratio and the Fine Aggregate Angularity (FAA). The density achieved at the initial and design number of gyrations for each mix is also shown (Gmm @ N_{init} and N_{des}, respectively). The requirements above meet the WisDOT's specifications for volumetric mix design (WisDOT. 2000).

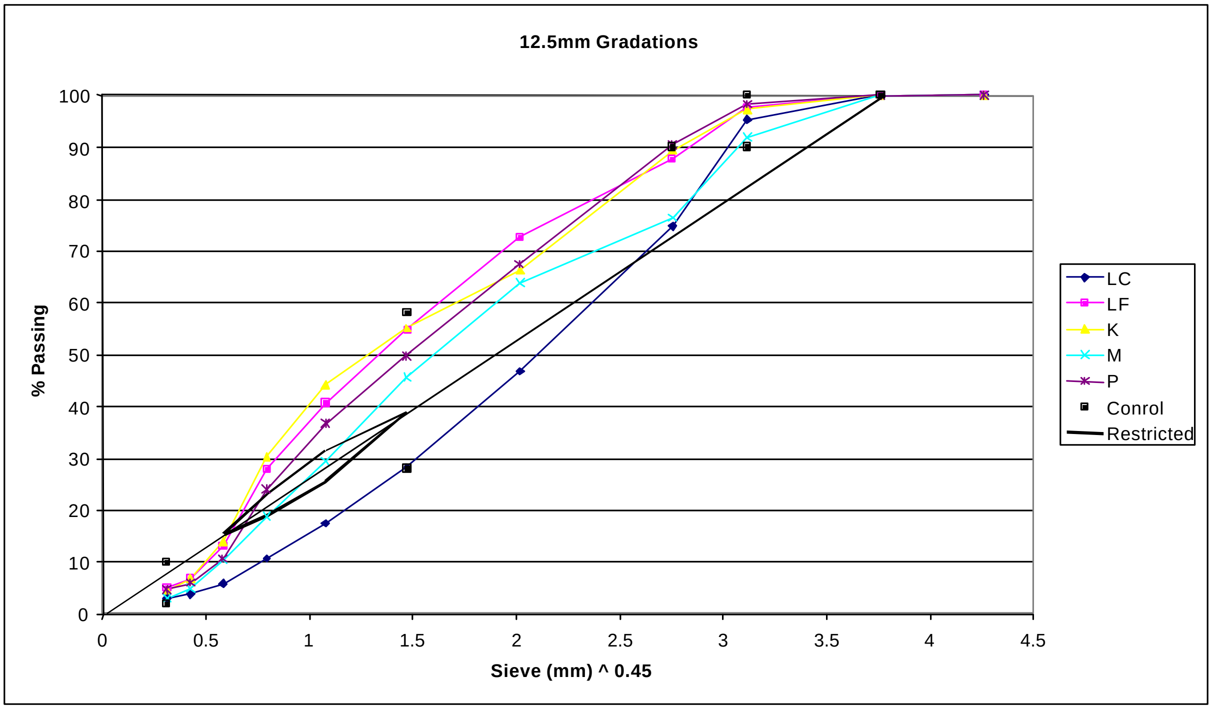


Figure 4.1. 12.5mm Mixture Gradation Plot

In Figure 4.1, the gradations of the various mixes used for the study are shown. It can be seen that only mixture LC, the coarse mixture from Source L, can be considered a coarse gradation. All of the rest of the gradations can be classified as fine, with the gradation lines passing above the bolded maximum density line.

Table 4.3. 19mm Mix Design Properties

	Source					
	LC	**LF**	**K**	**M**	**N**	**P**
Sieve	**Gradation**					
25	100	100	100	100	100	100
19	98.2	98.2	98.4	98.4	99.1	98.9
12.5	88.8	89.6	88.3	78.6	86.3	88.7
9.5	76.4	81.7	79.8	61.5	76.9	80.8
4.75	46.5	63.5	57.6	39.2	55.7	59.3
2.36	29.3	39.7	47.9	28.8	41	43.6
1.18	18.7	25.1	38.2	20.4	31.7	32.1
0.6	11.8	15.6	26.2	14.4	21.2	20.9
0.3	6.3	8.1	11.8	9.2	8	9.1
0.15	4	5	5.4	6.1	4.3	5.2
0.075	3.2	3.9	3.6	4.3	3	4.1
Volumetric Properties						
%AC	4.6	6.1	4.6	4.7	4.2	5.1
VMA	13.6	15.3	13.6	14.2	13	13.8
VFA	70.5	74.1	70.6	71.8	69.2	71
Dust/Binder	0.9	0.6	1	1	1	1.1
FAA	45.5	45.6	41.8	47.5	44.6	43.1
Gmm @ N_{init}	85.8	85.7	89.9	86.7	88.8	89.7
Gmm @ N_{des}	96	96	96	94.5	96	96
PG Grade	64-22	58-28	58-28	58-28	58-28	58-28

Table 4.3 shows the gradation and volumetric properties for the 19mm mixtures used in the project. All of the mix properties meet the requirements of WisDOT for volumetric mix design (WisDOT. 2000).

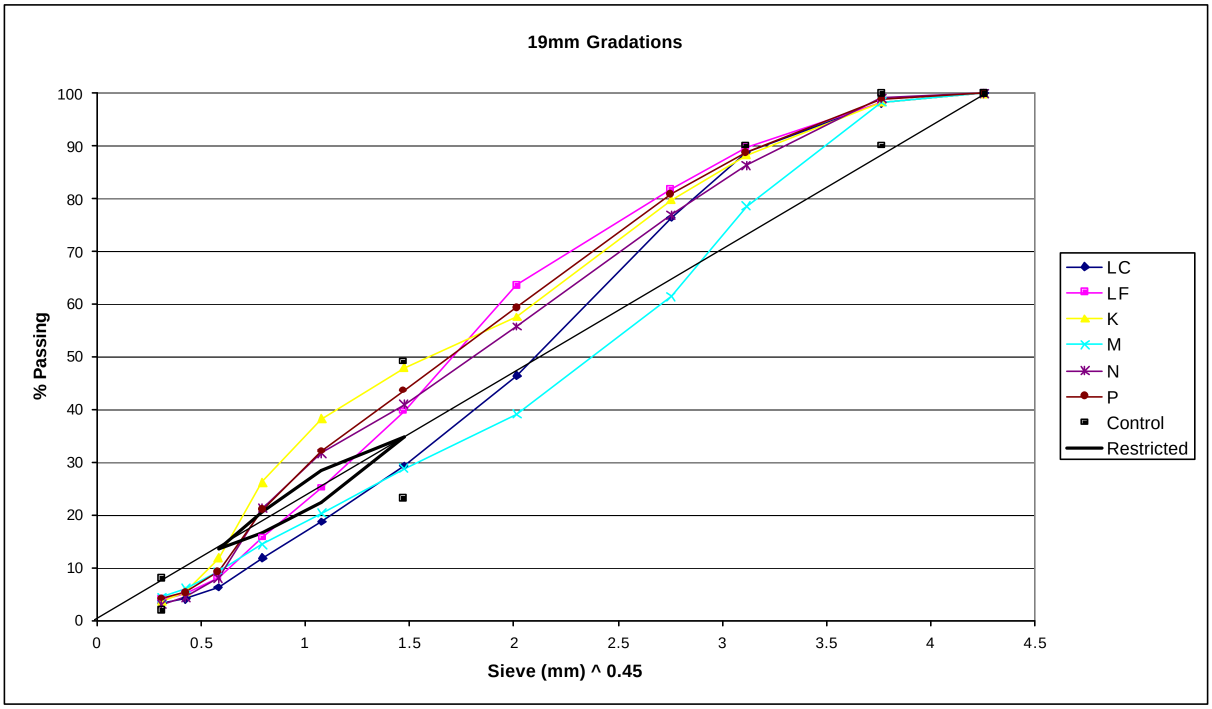


Figure 4.2. 19mm Mixture Gradation Plot

Figure 4.2 shows the gradations of the 6 different 19mm mixes tested as part of this study. Gradation LC, from Source L, and gradation M, from Source M, fell below the restricted zone, qualifying them as dense graded mixtures. The rest of the gradations pass above the restricted zone, classifying them as fine gradations.

The 12.5 and 19mm LF gradations, designed at the University of Wisconsin, both pass through the restricted zone. The information coming from the National Center for Asphalt Technology (NCAT) states that the restricted zone is no longer necessary for Superpave mix designs (Kandhal. 2001). Since the material from Source L could not design a mix to meet WisDOT's requirements without passing through the restricted zone, the decision was made to pass through the restricted zone in order to meet the remaining volumetric requirements.

The experiment does not cover all of the possible mix designs available in Wisconsin, for several reasons. First, the experiment was dependent on the projects that the state and the contractors agreed to allow experimentation on. Second, the study resources were not large enough to encompass all of the different possible experimental combinations. Therefore, a sampling scheme that removes some of the possible blocking effects (e.g., using only fine graded gravels or coarse graded limestones) was established. Attempts were made to sample projects from around the state in order to test all the types of aggregates used in Wisconsin. This attempt was somewhat successful, except for the fact that no projects were obtained from northern Wisconsin (north of Highway 29).

Table 4.4 shows the number of Equivalent Single Axle Loads (ESAL's) that each mix was designed for. Even though mostly E3 (designed for 3 million ESAL's of loading) and E10 (designed for 10 million ESAL's of loading) mixtures were used, this can be considered a good representative sample. E3 mixtures are commonly used on state highways, and E10 mixtures are used on more heavily trafficked roads, like interstates or higher volume state roads.

Table 4.4. ESAL's Sampled

	Material Type	Crushed Stone				Gravel			
	Gradation Type	Coarse		Fine		Coarse		Fine	
	Nom. Max. Size	19mm	12.5mm	19mm	12.5mm	19mm	12.5mm	19mm	12.5mm
Source	K							E3	E3
	L	E10	E10	E10	E10				
	M	E10			E10				
	N			E10					
	P			E3	E3				

4.2 TESTING SETUP

The objective of this study was to determine how lift thickness affects compaction resistance and density. The study by Hall et al. (1997) used differing sample sizes in order to study how sample size effected compaction in the SGC (Hall et al. 1997). Using this as a basis, it was determined that sample sizes of 1,500, 2,000, 3,000, 4,700 and 6,000 grams would be used in this study. By using the maximum range of sizes that the SGC could handle gave a wide spectrum of sizes to see how different lift thicknesses affects densification in the SGC. These results were then compared to the field compaction results for analysis and possible development of lift thickness criteria.

In order to develop a model to analyze how the different sample sizes affected the compactive resistance of the mixes, the Gyratory Load Plate Assembly was used on some of the samples compacted to the highest number of gyrations. By measuring the response given by the plate, the team was able to model the differences between samples to define the increase in compaction resistance caused by the sample thickness. The software used to analyze the data gathered from the GLPA is organized to allow for analysis of the shear resistance information obtained from the mixture itself, and for analysis of the area under the densification curve for the amount of energy needed to achieve densification in the construction and traffic stages of compaction. The analysis software provided enough information to determine occurrence within the mixture and how thickness affects the resulting output.

Another issue of concern with compacting thinner lifts of Superpave HMA’s has been the crushing of aggregates. It is believed that if mixtures are difficult to compact, additional densification is achieved at the cost of the aggregate structure, where the larger aggregates begin to fracture under load. In order to see whether this is in fact occurring, extractions were performed on the compacted samples of different thicknesses to evaluate if the sample size has an effect on aggregate crushing under compaction.

4.3 LABORATORY RESULTS FROM SGC COMPACTION (VOID AND DENSITY ANALYSIS)

Samples were batched in the five different sizes listed in the previous section (six different sizes for the Source L coarse gradations), and then compacted using the SGC according to AASHTO MP2 design procedures (AASHTO. 2001). Two samples at each of the five specimen sizes listed above were compacted to N_{des} (design number of gyrations as determined by WisDOT specifications). A third sample was compacted to N_{max} (maximum number of gyrations as determined by WisDOT specifications) or 200 gyrations (as was the case for only the Source L course mixtures). The percent air voids, determined by standard AASHTO and WisDOT procedures, at selected gyrations versus the ratio of lift thickness to nominal maximum size were then plotted.

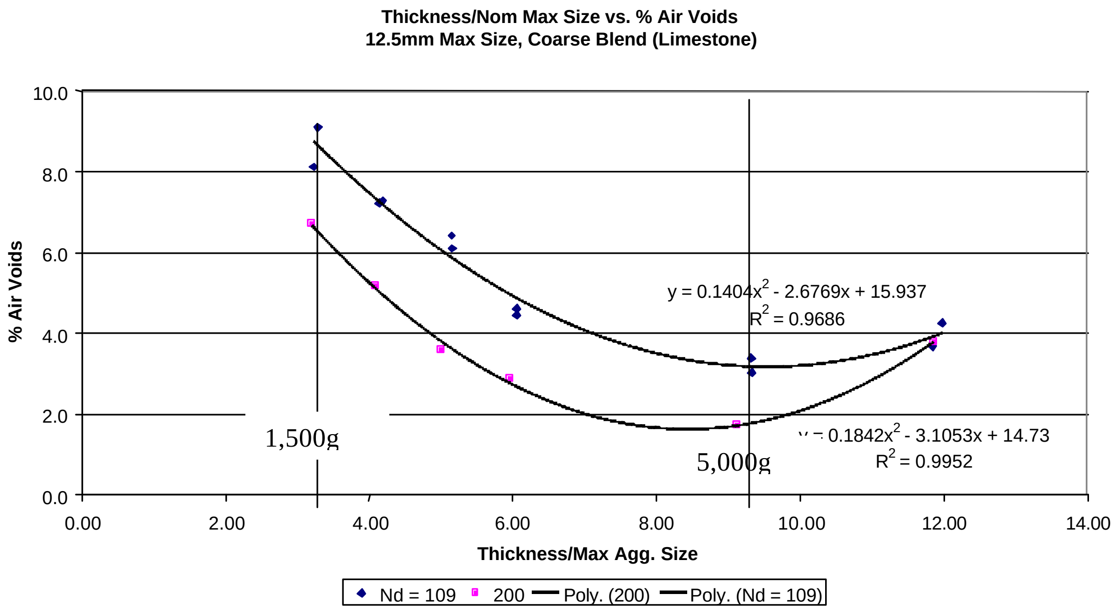


Figure 4.3. 12.5mm Coarse Limestone Plot

In Figure 4.3, the air voids measured for an E10-12.5mm mix produced with limestone were compacted to N_{des} and 200 gyrations are shown as a function of the ratio of sample thickness to maximum aggregate size. Thickness over the nominal maximum aggregate size was chosen for the abscissa since that is what is used by WisDOT to recommend HMA layer thickness. Polynomial trend lines are added for each set of gyration levels as a tool of modeling how air voids would change with changing the sample thickness for a given aggregate size.

As can be seen in Figure 4.3, samples with a ratio of 6 or less are more difficult to densify for this mixture. The thinnest samples, with ratios approximately 3.2, or a thickness of just over 1.5 inches and sample mass around 1,500-grams, had the highest air voids, averaging 8.6% at N_{des} compared to 4.5% at a ratio of 6, and 3.5% at a ratio of 9. As the E10 mixture sample thickness increased , the air void percentage decreased, reaching an optimal low at just over 9 times the nominal maximum aggregate size. This also correlates with the 5,000-gram sample size, as can be seen by the line drawn in Figure 4.3. The interesting fact is that the optimal amount of air voids was not reached until a ratio greater than the high end of the WisDOT specification (6) was reached. By increasing the compactive effort from 109 gyrations to 200 gyrations, the air voids are decreased by approximately 2% at all thicknesses except samples with ratios of 12.

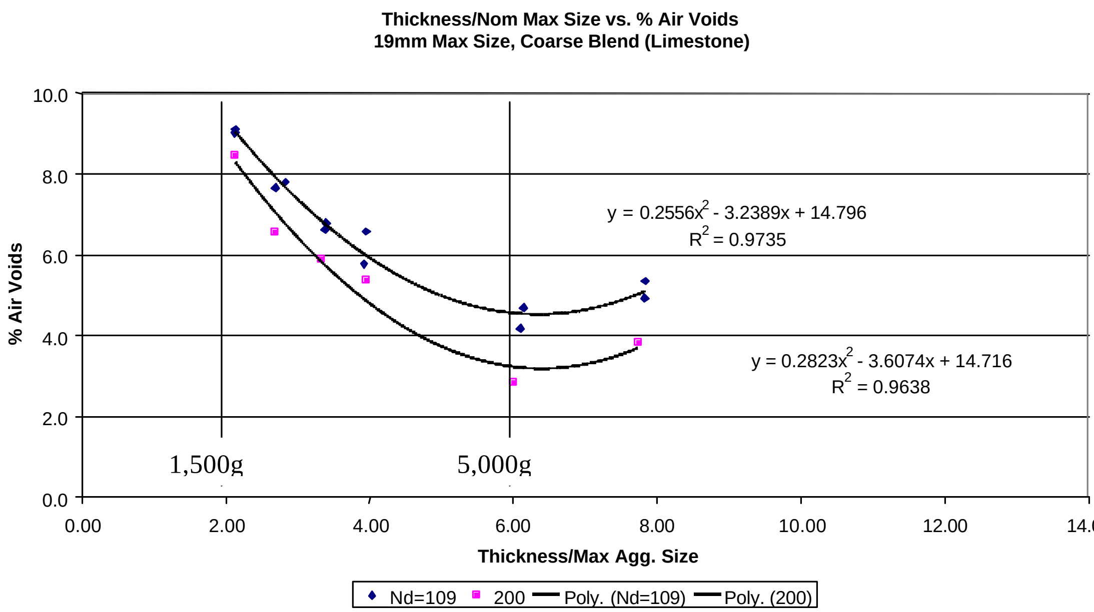


Figure 4.4. 19mm Coarse Limestone Plot

Figure 4.4 shows a similar plot for a 19mm coarse limestone E10 mixture instead of a 12.5mm E10 mixture shown in Figure 4.3. Both mix designs came from the same source and using the same types of materials. Although the same trend is seen in Figure 4.4, the trends are shifted to the left of the scale. Part of the shift results from plotting the information as a function of the thickness divided by the nominal maximum aggregate size. The trend for 19mm nominal maximum aggregate size shows air voids at about 9% for the samples with a ratio of around 2, or a thickness of about 1.5 inches. This trend decreases as the ratio increases until a ratio of 6 is observed, corresponding to a sample size of approximately 5,000 grams. By increasing the gyrations from 109 to 200, the air voids decrease by about 1% at all ratios.

Similar effects of thickness were seen for the other limestone mixtures produced by sources N and P. Some showed more extreme changes in air voids as a function of nominal maximum aggregate size, while others indicated less extreme trends. It was however, observed that all mixtures were comprised of higher air voids with sample sizes smaller than the 5,000-gram standard sample used in the SGC.

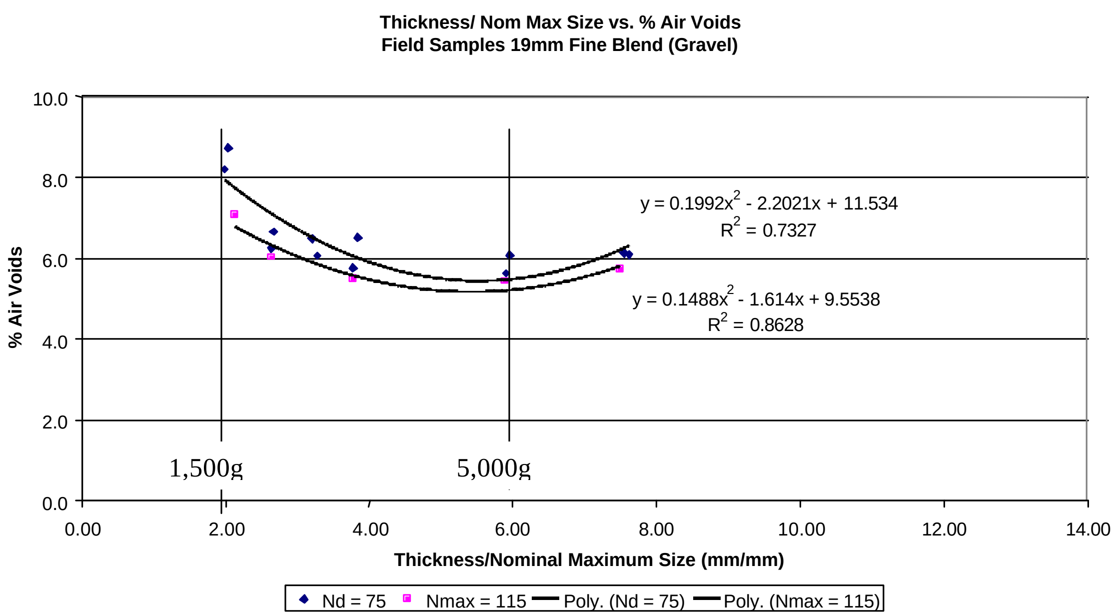


Figure 4.5. 19mm Fine Gravel Plot

Figure 4.5 depicts the results for the E3 fine gravel mixture from Source K. A similar trend of increasing air voids with lower thickness / size ratio is also evident, but the rate of change is less extreme and it appears that this mixture did not achieve 4% air voids at any sample size. It should be mentioned that the material for these compactions was obtained from the field. The plant quality control indicated that the mixture was running at high air voids during the day, resulting in the upward shift of the curves shown in Figure 4.5. The most important feature of this plot is that this mixture shows less sensitivity to sample size compared to the limestone mixtures provided in Figures 4.3 and 4.4.

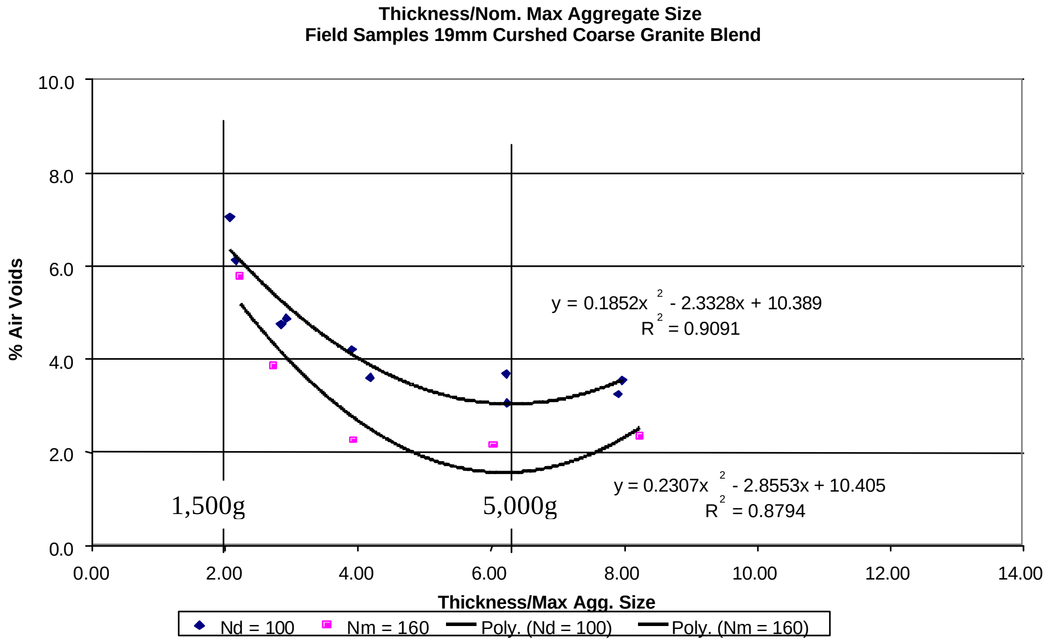


Figure 4.6. 19mm Coarse Granite Plot

Figure 4.6 shows the trends measured for a 19mm coarse graded crushed granite blend. The Quality Assurance at the plant that produced this mix was showing lower than required air voids on the day of sampling. The E10 mix curves from Source M, shows curves similar to the ones seen in Figure 4.4. High air voids are seen with the smaller samples, with the minimum measured around a ratio of 6, correlating to the 5,000-gram sample size. Increasing the compactive effort from N_{des} to N_{max} decreased the air voids by about 1.5% at all sample sizes.

The results identified in these curves are representative of what was observed throughout the project. Similar plots for the other mixtures are provided in Appendix B, with also the corresponding data tables.

Based on the air voids versus sample thickness to nominal maximum aggregate size ratio, it is clear that sample size appears to have an important effect, primarily observed for sizes below 5,000g and a ratio 9 for the 12.5mm mixes, and a ratio of 6 for the 19mm mixes.

4.4 RESULTS FROM THE GYRATORY LOAD PLATE ASSEMBLY

As mentioned earlier, they Gyratory Load Plate Assembly was used to measure shear resistance in order to see if shear resistance can be used to explain what is occurring during the compaction of these various sample sizes. As was explained in Chapter 2, by looking at the area under the densification curve from N_{init} to 92% G_{mm}, the Construction Energy Index (CEI) can be found and used as a measure of how difficult it is for each of these various mixes to be compacted in the field. By looking at the same area under the frictional resistance, or work curve generated by the GLPA, the Construction Friction Index (CFI) can be determined. The CEI area is a function of percent G_{mm} and gyrations, while the CFI is a function of the work to compact the mixture, measured in kPa, and the gyrations. Both analytical tools provide important information about the resistance of each mix to densification, as well as the resistance sensitivity to the type of mix, sample size, and nominal maximum aggregate size.

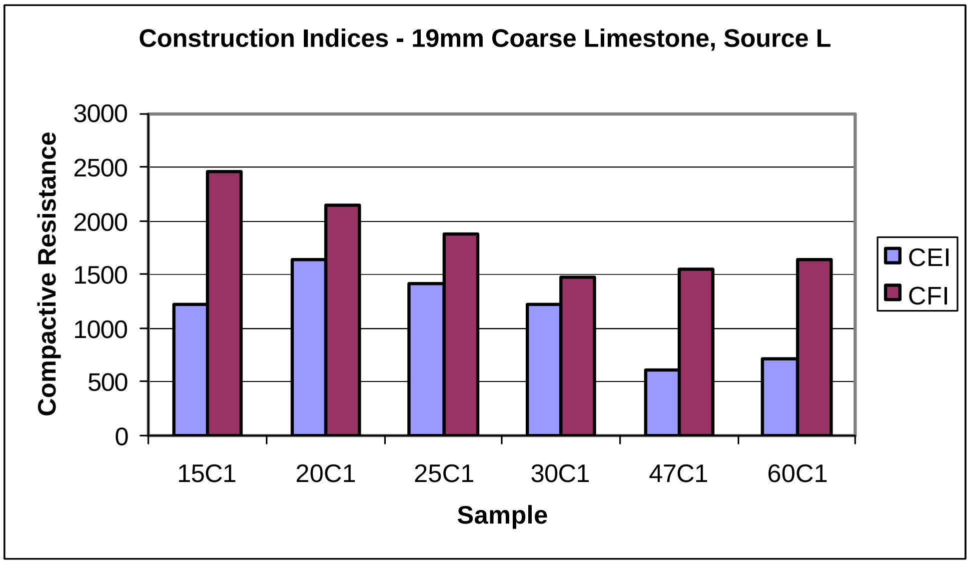


Figure 4.7. Construction Indices for 19mm Coarse Limestone Mixture

Figure 4.7 shows the compactive resistance as measured by the CEI and the CFI for the 19mm coarse limestone E10 blend from Source L. This figure shows that the 1,500-gram sample (15C1 in the figure) required more compactive resistance than the other sample sizes. Generally, the CEI's decreased with increasing sample size, with the exception of the 1,500-gram sample, which had a lower CEI than the 2,000-gram sample. The resistance increased slightly with the 6,000-gram sample when compared to the 4,700-gram sample. The effect of sample size is significant and could result in increasing the CEI by 65% when sample size changes from 3,000-grams to 1,500-grams. The friction index, CFI, is shown to be more sensitive and changes form 600 Kpa for the 4,700-gram sample to 2,600 Kpa for the 2,000-gram, which represents an increase of more than 300%. Although the relationship between these indices and field compaction is not well known, the observed change in indices suggests that smaller samples are more resistive to densification, which could explain the increase in air voids discussed earlier.

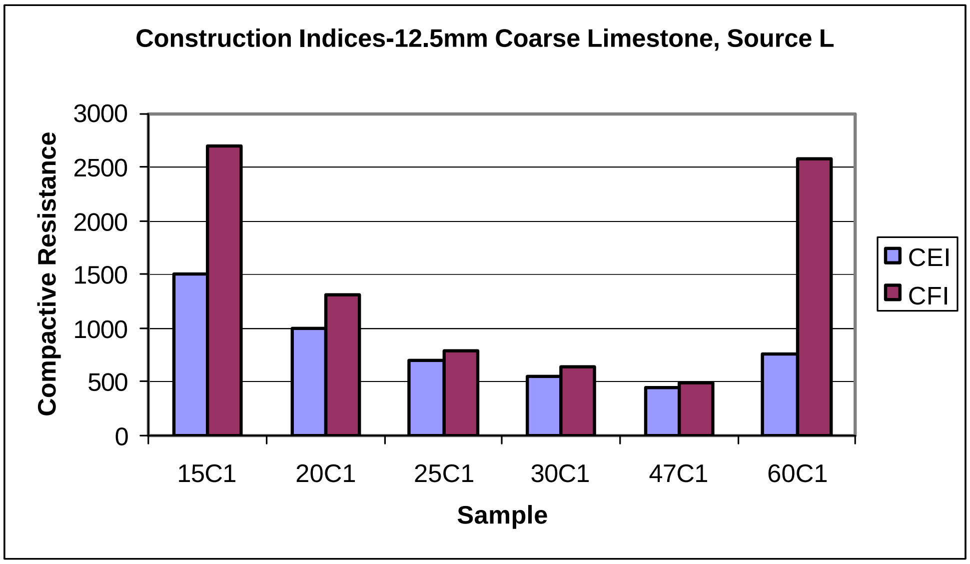


Figure 4.8. Construction Indices for 12.5mm Coarse Limestone

A different trend is demonstrated in Figure 4.8 for the 12.5mm limestone mix. It is observed for this mix that the compactive resistance decreases with increasing sample size until the 4,700-gram sample (47C1). Again, the resistance increases for the 6,000-gram sample size, this time by a factor of five for the CFI. The trends seen in this E10, 12.5mm mixture are more extreme than those seen in the 19mm coarse limestone data set. The CEI values are generally higher than those observed for the 19mm counterpart, and the CFI start about the same, but decrease more drastically.

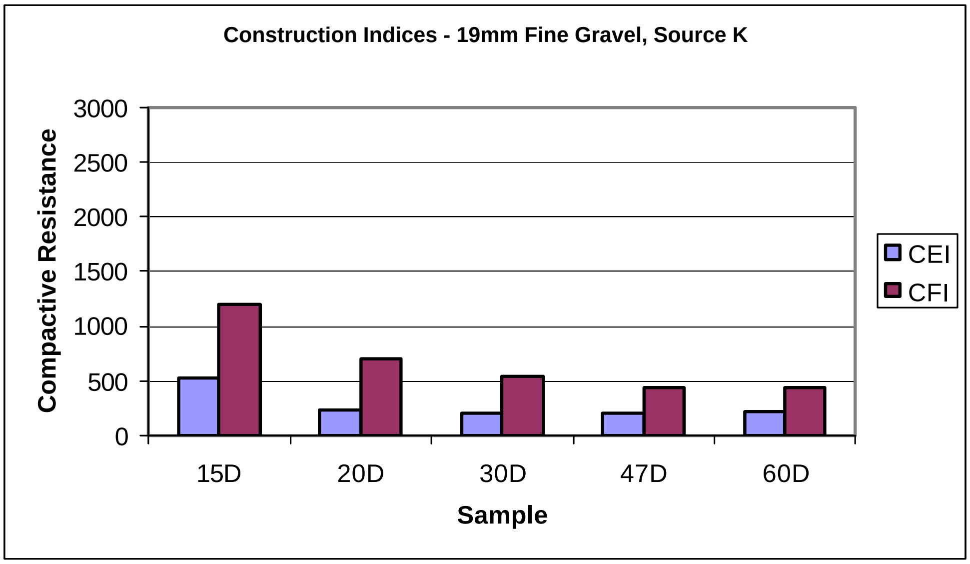


Figure 4.9. Construction Indices for 19mm Fine Gravel

The fine gravel E3 mixture modeled in Figure 4.9 demonstrated significantly less compactive resistance on both scales than did the limestone mixtures depicted previously. The trend for the CEI is significantly flatter than what was seen for the limestone mixtures. While the trend for the CFI was not as flat as the CEI, it was still less pronounced than those seen for the 19mm mixes.

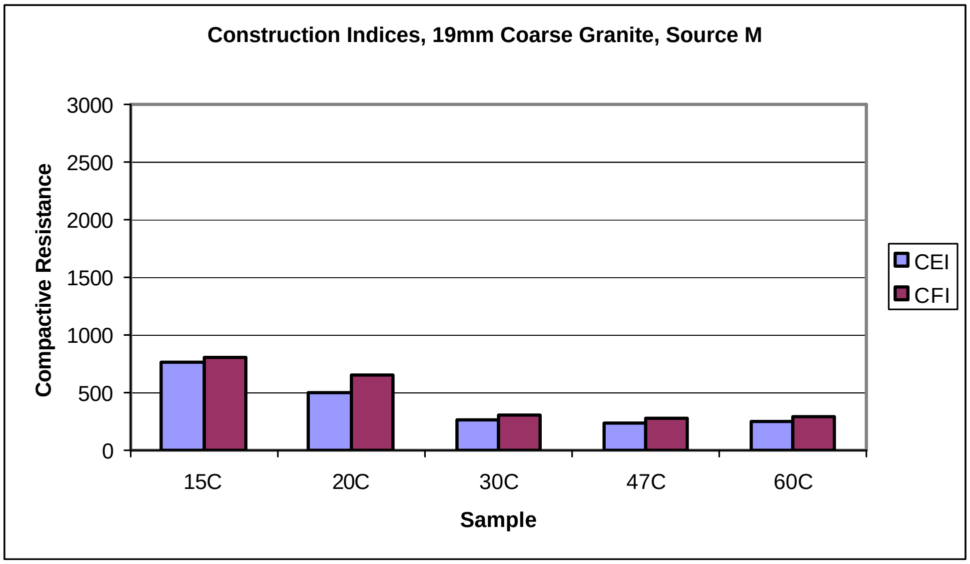


Figure 4.10. Construction Indices for 19mm Coarse Granite

Figure 4.10 depicts the construction indices from Source M. The results for the E10 coarse granite mixture shows a trend that is similar to those observed for the gravel mixture shown in Figure 4.9. Both indices are relatively low compared to the limestone mixtures, and slightly lower than the trends seen for the gravel mixture in Figure 4.9.

Although the values for this mix are relatively low, it was generally observed that the 1,500-gram sample was more resistant to compaction than the remaining samples.

The results of the construction indices demonstrated that variations in mixture composition result in differing resistance to compaction. Analysis of all mixtures indicate that smaller samples offer more resistance to compaction than larger sample sizes . Results further indicate that the limestone coarse and fine mixes offer more resistance to compaction for all sample sizes; with greatest resistance noted for smaller samples. For all mixes, it appears that there is only a marginal effect for samples above 3,000-grams. The sample effect was much higher for the 1,500-gram and the 2,000-gram samples. Based on this collective analysis, it appears that the thickness effect may be disregarded above a ratio of lift thickness to nominal maximum aggregate size within the range of 4-6; dependent on the nominal maximum aggregate size of the mix.

A complete set of plots and values obtained from the GLPA for all of the mixes tested is provided in Appendix C.

4.5 STATISTICAL ANALYSIS

4.5.1 Introduction to Analysis Tools

Due to the extensive amount of data gathered as part of this study, various statistical analyses were used to determine if the effects of certain variables in the study were significant in comparison to specific measured responses. The most common model used was the Analysis of Variance (ANOVA) model. The ANOVA model was useful to this analysis because it relates the independent, or control variables, such as gradation and source to the dependent, or response, variables such as CEI, and percent air voids. An ANOVA analysis applies the variances between and within samples to calculate the validity of an experimental setup. By pooling the differences for the entire experiment and between the samples, a method of measuring the significance of the test results is obtained (Johnson. 1994). ANOVA generates p-values, which calculate the statistical significance of specific results relating to the affects a dependent variable has on an independent variable (Netter et al. 1985). Statistically, the meaning of p-values can be described as follows:

1) p-value < 0.001 = Very Strong Evidence
2) 0.001 < p-value < 0.01 = Strong Evidence
3) 0.01 < p-value < 0.05 = Moderate Evidence
4) 0.05 < p-value < 0.10 = Weak Evidence

For the purposes of this study, a p-value of 0.05 (Moderate Evidence) was determined to be the significance limit. This assured that any variable having no significance on the ANOVA matrix would be removed, and that any variable providing some effect would be considered as part of the analysis.

The statistical program Statistical Analysis System (SAS) was used to run the ANOVA analysis of the data in the project. The SAS program allows expressing the relationship between the independent variables and the dependent variables;. At the same time, the program can provide a R^2 value for the analysis to determine how accurately the change in dependent variables could be explained by the independent variables. Higher R^2 values indicate a better explanation of the dependent (such as density) by the independent variables (such as thickness and aggregate type).

4.5.2 Statistical Setup

Before statistical analyses are conducted, the response (dependent) variables must be be selected. Each of the previously plotted curves showed decreasing air voids with increasing specimen thickness. The highest level of air voids was observed with the thinnest samples, at 1,500-grams. The percentage of air voids generally decreased until they reached the 3,000 gram sample size, and from there, the trend flattened until it reached sample sizes of 6,000 grams or more. Since there is a natural inflection at 3,000 grams, this became the logical point of reference for the analysis. In addition, the ratio of lift thickness to nominal maximum aggregate size that is closest to the WisDOT's specification is the 3,000 gram sample size. The ratio for the 19mm mixes is approximately 4, while for 12.5mm mixes it is approximately 6. Even though these were slightly above the DOT's specification, the 3,000 gram sample size offered the closest to the target size in the gyratory compactor. Therefore, the 3,000 gram sample size was used as the point of reference for the statistical analysis in order to relate the optimal conditions in the field to the SGC.

In order to capture how the different gradations, nominal maximum aggregate sizes, design ESAL's and aggregate sources affected the compaction results, ratios of responses measured at various sample sizes to the response of the 3,000 gram sample were used. It was determined that using these ratios would normalize the effect of mixture volumetric design values specific to each mixture. In order to find out how thin samples affected the different responses, the ratios of air voids for the 1,500 gram samples to the air voids for the 3,000 gram samples were used as the response. Much in the same way, by looking at the ratio of air voids for the 6,000 gram sample to the 3,000 gram sample, the effect of thicker samples can be determined.

The following example should help explain this approach. Given the following:

% Air Voids for 1500g = 8%
% Air Voids for 3000g = 4%
% Air Voids for 6000g = 4%

In this case, that base of comparison established was the 3000 gram sample. The ratio of air voids for 1500g/3000g is 8%/4% or 2.0, and the ratio of 6000g/3000g is 4%/4% or 1.0. A value close to 1 for this study means that there is little difference between the point of analysis and the base point value from the 3,000 gram sample. A value less than 1 means that the numerator (1500g or 6000g) is less than the base of comparison, while a value greater than 1 means that the numerator value is greater than the base of comparison. The further the values are from 1, the more significant the difference.

In addition to the air voids, other dependent response variables were analyzed. In the field, 92% of the G_{mm} is often the target for compaction of the HMA mats. In order to make a more valid comparison of the laboratory to the field, the number of gyrations necessary for compaction to 92% G_{mm} was compared. The results were used to provide a more direct comparison of density from the lab to the field.

In order to determine the energy of compaction and the resistance provided by the mixtures, the CEI and CFI was analyzed using the ratios of the 1500 gram to the 3000 gram samples, and the 6000 gram to the 3000 gram samples. Four response variables were analyzed: (1) % air voids and N_{des}, (2) number of gyrations to 92% G_{mm}, (3) CEI, and (4) CFI. In order to perform initial cursory analyses, the ratios have been organized into the following experimental setup Tables 4.5 to 4.9.

Table 4.5. Air Voids Ratios for 1500g/3000g

	Material Type	Crushed Stone				Gravel			
	Gradation Type	Coarse		Fine		Coarse		Fine	
	Nom. Max. Size	19mm	12.5mm	19mm	12.5mm	19mm	12.5mm	19mm	12.5mm
Source	K							1.26	1.69
	L	1.39	1.76	1.98	1.31				
	M	1.95			1.69				
	N			1.76					
	P			1.55	1.76				
	Average	1.67	1.76	1.76	1.58			1.26	1.69

Table 4.6. Air Void Ratios for 6000g/3000g

	Material Type	Crushed Stone				Gravel			
	Gradation Type	Coarse		Fine		Coarse		Fine	
	Nom. Max. Size	19mm	12.5mm	19mm	12.5mm	19mm	12.5mm	19mm	12.5mm
Source	K							0.94	1.13
	L	0.75	0.92	0.94	0.89				
	M	0.98			1.13				
	N			0.96					
	P			0.95	1.18				
	Average	0.87	0.92	0.95	1.06			0.94	1.13

Tables 4.5 and 4.6 provide a list of the ratios of air voids for 1500g/3000g and 6000g/3000g. The range values of the 1500g/3000g fall between 1.26 for the 19mm gravel mixture to 1.98 for the 19mm fine crushed stone. Due to the limited data, no specific trend was discerned. The results do indicate, however, that changes in the sample size from 1,500 grams to 3,000 grams had an impact. A review of the 6,000g/3000g ratios provided in Table 4.6, clearly indicates that most values range from a low of 0.75 to a high of 1.18, with the majority close to 1; indicating that the difference in percent air voids for the thicker sample to the 3,000 gram base sample is small. The same kind of analysis was performed for the ratios of the number of gyrations necessary to achieve 92% G_{mm} that are shown in Tables 4.7 and 4.8.

Table 4.7. Gyration Ratios for 1500g/3000g

	Material Type	Crushed Stone				Gravel			
	Gradation Type	Coarse		Fine		Coarse		Fine	
	Nom. Max. Size	19mm	12.5mm	19mm	12.5mm	19mm	12.5mm	19mm	12.5mm
Source	K							2.07	1.05
	L	1.10	2.61	3.52	3.52				
	M	2.64			3.18				
	N			4.38					
	P			3.61	2.41				
	Average	1.87	2.61	3.84	3.04			2.07	1.05

Table 4.8. Gyration Ratios for 6000g/3000g

	Material Type	Crushed Stone				Gravel			
	Gradation Type	Coarse		Fine		Coarse		Fine	
	Nom. Max. Size	19mm	12.5mm	19mm	12.5mm	19mm	12.5mm	19mm	12.5mm
Source	K							1.14	0.58
	L	0.53	0.93	1.28	1.04				
	M	1.04			1.28				
	N			0.94					
	P			1.18	0.95				
	Average	0.78	0.93	1.13	1.09			1.14	0.58

Trends provided in Tables 4.7 and 4.8 indicate similarities to those witnessed for the percentage of air voids; with values greater than 1 discernible for the ratio of 1500g/3000g. As part of this analysis, the range of results were more extreme, with some close to 1 to values above 4. These results demonstrate the extreme difference in the number of gyrations necessary to achieve 92% G_{mm}. For the 6000g/3000g ratio analysis, the results were again around 1, signifying that on the thicker side, there is only a marginal difference in the number of gyrations necessary to achieve 92% G_{mm}.

In general, the gyration ratios mimic the trends observed for air voids with regard to the effect of sample size. The 1,500 gram samples require more gyrations with ratios ranging from 1.10 to 4.38 relative to the 3,000 gram samples, while the 6,000 gram samples require approximately the same number of gyrations as the 3,000 gram samples. Exceptions noted in the trends for the 6,000 gram samples included mixtures for the 12.5mm gravel mix and the 19mm crushed stone. In these cases, ratios of 0.58 and 0.53 are displayed. The variation in the ratio of air voids achieved at N_{des} gyrations (Tables 4.5 and 4.6) and the ratios of gyrations to 92% G_{mm} clarify that the sample size effect is highly dependent on source, maximum aggregate size and aggregate type.

CEI ratios are listed in Tables 4.9 and 4.10 these ratios are thought to provide a more specific measure of resistance to densification to 92% G_{mm}. These indices represent the combined effect of number of gyrations and rates of change in air voids. Tables 4.11 and 4.12 list the CFI ratios, which represent the mixture viscosity (resistance to shear) measured directly by total force required to achieve 92% G_{mm} measured in the SGC. The results shown in the four tables confirm that smaller sample sizes require more compaction energy than larger sample sizes for all mixtures. The results, however, demonstrate that the change relative to the 3,000 gram sample varies significantly among the mixture types and do not follow a specific trend.

Table 4.9. CEI Ratios for 1500g/3000g

	Material Type	Crushed Stone				Gravel			
	Gradation Type	Coarse		Fine		Coarse		Fine	
	Nom. Max. Size	19mm	12.5mm	19mm	12.5mm	19mm	12.5mm	19mm	12.5mm
Source	K							2.61	2.29
	L	1.01	2.74	2.28	3.11				
	M	2.97			2.75				
	N			5.67					
	P			4.97	2.86				
	Average	1.99	2.74	4.31	2.91			2.61	2.29

Table 4.10. CEI Ratios for 6000g/3000g

	Material Type	Crushed Stone				Gravel			
	Gradation Type	Coarse		Fine		Coarse		Fine	
	Nom. Max. Size	19mm	12.5mm	19mm	12.5mm	19mm	12.5mm	19mm	12.5mm
Source	K							1.12	0.39
	L	0.59	1.37	1.52	0.95				
	M	0.95			1.11				
	N			0.88					
	P			1.20	0.77				
	Average	0.77	1.37	1.20	0.94			1.12	0.39

Table 4.11. CFI Ratios for 1500g/3000g

	Material Type	Crushed Stone				Gravel			
	Gradation Type	Coarse		Fine		Coarse		Fine	
	Nom. Max. Size	19mm	12.5mm	19mm	12.5mm	19mm	12.5mm	19mm	12.5mm
Source	K							2.24	1.35
	L	1.67	4.18	1.64	3.19				
	M	2.71			2.64				
	N			4.61					
	P			3.81	2.45				
	Average	2.19	4.18	3.36	2.76			2.24	1.35

Table 4.12. CFI Ratios for 6000g/3000g

	Material Type	Crushed Stone				Gravel			
	Gradation Type	Coarse		Fine		Coarse		Fine	
	Nom. Max. Size	19mm	12.5mm	19mm	12.5mm	19mm	12.5mm	19mm	12.5mm
Source	K							0.81	0.38
	L	1.10	3.99	0.97	0.98				
	M	0.97			1.05				
	N			0.93					
	P			0.95	1.02				
	Average	1.04	3.99	0.95	1.02			0.81	0.38

In summary, analyses of the ratios indicate that the effect of lift thickness (sample size) on density measured in the lab cannot be considered by using one formula. In other words, the minimum lift thickness to nominal maximum aggregate size that would achieve the target density is highly dependent on the specifics of the mixture being compacted. It remains to be determined, however, which of the mixture characteristics has a significant role and which could be considered unimportant. The significance of the different mixture characteristics may be best evaluated by conducting statistical analyses as discussed in the next section.

4.5.3 Statistical Analysis

As part of this analysis, several response and control variables were selected. The four response variables and six independent (control) variable selected for this study are listed in Table 4.13.

Table 4.13. Variable Setup

	Control Variables	Level 1	Level 2	Response Variables (all in ratios)
1	Gradation (G)	Coarse	Fine	% Air Voids @ Ndes
2	Nominal Maximum Size (S)	19mm	12.5mm	Gyrations to 92% Gmm
3	Rock Type (T)	Crushed Rock	Gravel	CEI
4	Ratio (R)	1500/3000	6000/3000	CFI
5	Mix ESAL's (E)	E10	E3	
6	Replicate Run (D)	1	2	

As part of the ANOVA analysis, two different levels were selected and are also listed Table 4.13. The following sections describe the results of the statistical analyses for each of the response variables.

4.5.3.1 Analysis 1, Full Model

Table 4.14. Summary of the ANOVA Analysis for the ratio of Air Voids at N_{des}

Full ANOVA Model					
Source of Variation	*DF*	*Sum of Square*	*Mean Square*	*F-Value*	*Sig. Level*
Main Effects					
Gradation (G)	1	0.03	0.03	0.85	0.3639
Size (S)	1	0.20	0.20	6.52	0.0151
Ratio (R)	1	5.57	5.57	177.46	<.0001
ESAL (E)	1	0.01	0.01	0.18	0.6703
Run (D)	1	0.02	0.02	0.74	0.3956
Interactive Effects					
Gradation*Size (G*S)	1	0.14	0.14	4.40	0.043
Size*ESAL (S*E)	1	0.21	0.21	6.68	0.0139
					R^2 = 0.8402
Reduced Model - Main Effects Only					
Ratio (R)	1	5.57	5.57	154.45	<.0001
Run (D)	1	0.02	0.02	0.64	0.4272
					R^2 = 0.7909

In Table 4.14 provides the results for the dependent variable air voids resulting from the full ANOVA analysis. As part of the full analysis, both the main and two way interactive effects were considered for significance. As indicated, the ratio (R) of sample thickness to maximum aggregate size appears to be the most significant factor, in addition, for the main effects, the nominal maximum size (S) proved to also be important. The interactive effects of Gradation and Size (G*S), and Size and ESAL's (S*E) were also found to be significant. The R^2-value of 0.84 indicates that the model can explain the variation in ratio with a high level of confidence. Some of the effects that were not significant include whether the gradation was coarse or fine (G), the amount of traffic the road is designed for (E), and the replicates (D). Due to the significance of the interactive factors, ESAL's and Gradation were not removed from the model.

To simplify the model, only the ratio and replicates were used. In this reduced model, only the ratio proved to be significant. The removal of the interactive effects reduced the R^2 –value of the model, but only to 0.79, demonstrating that the interactive effects had a minor impact on the fit of the model. Therefore, while the mixture characteristics appeared to be important, they do not appear to be statistically significant when compared to the effect of sample thickness to nominal maximum aggregate size ratio.

Using similar analytical methods, the ANOVA results for all four response variables are listed in Table 4.15 for the main and two-way interactive effects. As indicated, the cells coded “No” had no significant effects, while the rest of the results with numeric values had significant results. The most significant result for all variables was the affect that the ratio of lift thickness to nominal maximum aggregate size played. The mixture type and replicate run are not significant for any of the response variables. The nominal maximum aggregate size shows some significance for the CFI and percent air voids. The remaining control variables had no significance for more than one response.

Table 4.15. Summary of Full Model ANOVA Results

Effect	Response Variable			
Main	**% Air Voids**	**Gyrations to 92%**	**CEI**	**CFI**
Gradation (G)	No	No	No	0.0011
Nom. Max Size (S)	0.0151	No	No	0.0002
Type (T)	No	0.0291	No	No
Ratio (R)	<0.0001	0.0001	<0.0001	<0.0001
Mix Type (M)	No	No	No	No
Run (D)	No	No	No	No
Interactive	**% Air Voids**	**Gyrations to 92%**	**CEI**	**CFI**
G*S	0.043	0.0281	No	<0.0001
G*R	No	0.0382	No	0.0342
G*D	No	0.0267	No	No
S*M	0.0139	No	No	No
R*M	No	0.0267	No	No
R*D	No	0.0279	No	No
R^2	0.8402	0.8685	0.6501	0.8107

Of the 15 interactive effects analyzed, only those indicated in Table 4.15 were significant. The interactive effect of gradation and nominal maximum size (G*S) was the most consistently significant effect. The gradation and ratio (G*R) also produced an interactive effect for two of the response variables.

In Table 4.16, the results of running the test without the interactive effects are shown. By removing the interactive results, some of the main effects were reduced from significant to not significant. The R^2-values of the models have also decreased with the removal of the interactive effects, particularly for the gyrations to 92% G_{mm} and the CFI responses. The effect of sample thickness to nominal maximum size ratios (R) remained significant as an interactive effect. The results for CEI didn't change from Table 4.15 to Table 4.16 due to the lack of interactive effects in the analysis of the full model.

Table 4.16. Summary of ANOVA of Main Effects Only, Full Model

Effect	**Response Variable**			
Main	**% Air Voids**	**Gyrations to 92%**	**CEI**	**CFI**
Gradation (G)	No	0.0014	No	No
Nom. Max Size (S)	No	No	No	No
Type (T)	No	0.022	No	No
Ratio (R)	<0.0001	<0.0001	<0.0001	<0.0001
Mix Type (M)	No	No	No	No
Run (D)	No	No	No	No
R^2	0.7909	0.553	0.6501	0.5782

It is important to note that the R^2-value in Table 4.16, which represent the ability of the independent variables to explain the change in response variable, decreased significantly. This observation coupled with the fact that even for the full models (Table 4.15), the R^2-value for the CEI was relatively low (0.650), made it necessary to explore other models in which additional levels were considered for selected independent variables. One of these variables (aggregate type (T)) has not been included at all possible levels. This is discussed as Analysis 2 in the following section.

4.5.3.2 Analysis 2, Aggregate Type Model

After running the full model, the next step was to evaluate whether the type of aggregate would be statistically significant. To conduct this analysis, the source properties used were increased to include consideration of not only the two levels crushed rock and gravel in the type category, but also crushed limestone, crushed granite, and crushed gravel; which were coded differently

Table 4.17 shows the change in R^2-values when resulting from the increase in aggregate type levels. Conclusions drawn from a comparison of these results to the analysis in Table 4.15, indicate that increasing aggregate types cause only minor improvements in the

R^2-values. In addition, there are only minor variations in the significance of certain main factors.

Table 4.17. Summary of Aggregate Type ANOVA Analysis

Effect	Response Variable				
Main	**DF**	**% Air Voids**	**Gyrations to 92%**	**CEI**	**CFI**
Gradation (G)	1	No	No	No	0.0057
Nom. Max Size (S)	1	0.015	No	No	0.0002
Type (T)	2	0.0314	No	No	No
Ratio (R)	1	<0.0001	<0.0001	<0.0001	<0.0001
Mix Type (M)	1	No	No	No	No
Run (D)	1	No	No	No	No
Interactive		**% Air Voids**	**Gyrations to 92%**	**CEI**	**CFI**
G*S	1	0.0018	0.0037	No	0.0002
G*R	1	No	0.0343	No	0.00363
G*D	1	No	0.0425	No	No
S*M	1	0.0012	No	No	No
T*R	1	No	0.0183	No	No
T*D	1	No	0.0197	No	No
R^2		0.8697	0.9079	0.6746	0.8217

Looking again at the main effects in Table 4.18, it is noted that the R^2-values for the reduced model are still lower than those identified when interactive effects are included. A significant improvement in the R^2-value for the gyrations to 92% G_{mm} was however noted.

Table 4.18. ANOVA of Main Effect Only, Aggregate Type Model

Effect	Response Variable			
Main	**% Air Voids**	**Gyrations to 92%**	**CEI**	**CFI**
Gradation (G)	No	0.087	No	No
Nom. Max Size (S)	No	0.0312	No	No
Type (T)	No	0.0209	No	No
Ratio (R)	<0.0001	<0.0001	<0.0001	<0.0001
Mix Type (M)	No	No	No	No
Run (D)	No	No	No	No
R^2	0.7934	0.7601	0.6501	0.5782

In summary, by considering the aggregate type an improvement in the models was characterized by an increase in the R^2-value for each response variable for the respective categories. Because this resulted in better models, another model type was used to analyze greater specificity in the levels of aggregate source used.

4.5.3.3 Analysis 3, Reduced Source Model

Since many of the factors listed previously were not statistically significant in many of the models, the final model selected was reduced to include only independent variables that had a significant effect on more than one response variable. Only two interactive effects were noted in more than one of the models: (1) gradation type with nominal maximum size (G*S), and (2) gradation type with the thickness ratio (G*R). Although Ratio (R) was the only main effect that was significant in more than one model, gradation (G) and nominal maximum size (S) were also included because of their noted significant interactive effects. In addition, because aggregate source appears to result in higher R^2-values, it was also included. The five different sources tested in this project were included in this last model. All other variables were considered at the same two levels used earlier.

Table 4.19. Final Model ANOVA Analysis

Effect	**Response Variable**			
Main	**% Air Voids**	**Gyrations to 92%**	**CEI**	**CFI**
Gradation (G)	No	No	No	0.001
Nom. Max Size (S)	No	No	No	<0.0001
Source (L)	No	No	No	No
Ratio (R)	<0.0001	<0.0001	<0.0001	<0.0001
Interactive	**% Air Voids**	**Gyrations to 92%**	**CEI**	**CFI**
G*S (G*S)	No	No	No	0.001
G*R (G*R)	No	No	No	0.03
R^2	0.8246	0.779	0.7762	0.8481
R^2 (Ratio Only)	0.7876	0.5891	0.6492	0.5616

The ANOVA results for the final selected model listed in Table 4.19 indicate that sample thickness to nominal maximum aggregate size ratio (R) is the only significant main factor for air voids, gyrations to 92% G_{mm}, and the CEI ratios. For CFI, it was found that gradation and size are also important. The remaining interactive effects are not important with the exception of the CFI ratios, for which the results show that gradation and source (G*S) is also significant.

It is also important to note that the R^2-values were all above 0.77, which represents a significant change when compared to the previous models. If the model was reduced to look at only the R^2-value only for Ratio, and nothing else in the model, the R^2-values decreased by differing amounts depending on the response ratio. This shows that even though the other control variables may not be statistically significant, they still have an effect on the model.

Overall, the most significant result was the ratio, resulting in high F-values, or low p-values for all response variables. Using the final model with all five sources resulted in a reduction of the interactive effects. Overall, using the five aggregate sources instead of the two or three generally improved the fit of the models.

The ANOVA analysis showed that ratio of different sample sizes are the most important factor in explaining the variation in the response variables. As a result, the next logical step was to look at how sample sizes affected the response variables. Because air voids are the most direct measures of compactibility, they were used to derive a regression model in terms of sample thickness to nominal maximum aggregate size. In order to do this, the raw data was used for all sample sizes. The model was fitted to all samples to determine how the ratio of sample thickness to nominal maximum aggregate size affected the density achieved during the compaction process in the SGC to N_{des}. Multi-linear regression analyses were performed on the entire data set to model the air voids at different sample sizes. This approach enabled the team to calculate the standard, and estimate the range of air voids within an appropriate confidence interval.

Table 4.20 provides the results of the multi-linear regression analysis. The important values are the R^2 and Confidence Intervals. The R^2-value of 0.59 is lower than was seen in the earlier model runs, and the Confidence Interval is broad, with a +/- of 2.14 for the air voids. This means that a range of 4.4% air voids around the target is necessary for 95% confidence. This is much wider than the state specifications for air void deviation in quality control testing.

Table 4.20. Multilinear Regression Model

Regression Statistics	
Multiple R	0.77
R Square	0.60
Adjusted R Square	0.59
Confidence Interval (95%)	+/- 2.14
Standard Error	1.09
Observations	110

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	190.83	95.41	79.90	5.91496E-22
Residual	107	127.78	1.19		
Total	109	318.61			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	10.25306794	0.48	21.47	0.00
X Variable 1	-1.464858363	0.17	-8.81	0.00
X Variable 2	0.081265293	0.01	6.67	0.00

The results may be interpreted as indicating that the model does not fit the data very well, and that there is high variability in the data set. This can be seen in Figure 4.11, by viewing the broad data point distribution around the model equation.

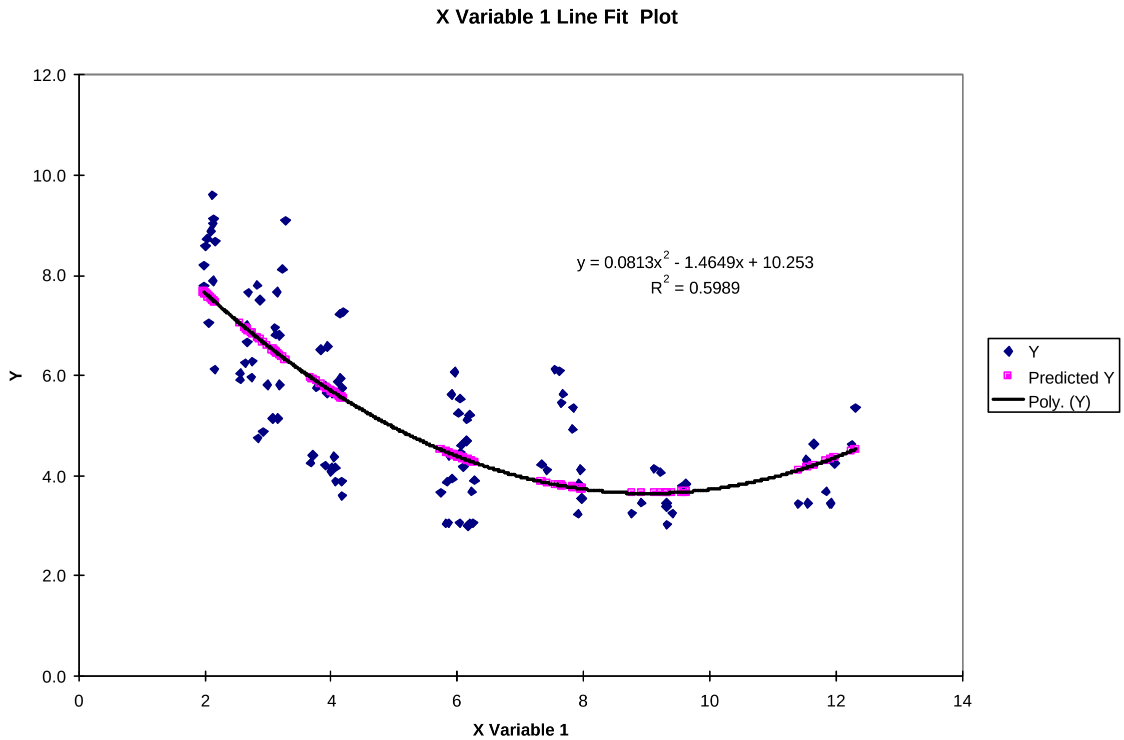


Figure 4.11. Regression Plot

As depicted in the plot, the data points have a large degree of vertical scatter; meaning that there is high variation in air voids at one sample size across the whole experiment. A similar analysis on the data for only one mix type, instead of all eleven, derives a better fitting model that conforms to the data. This was accomplished using the results from the Source L 12.5mm mix.

Table 4.21. Multilinear Regression for 12.5mm Coarse Limestone, Source L

Regression Statistics	
Multiple R	0.98
R Square	0.97
Adjusted R Square	0.96
Standard Error	0.39
Confidence Interval (95%)	+/- 0.77
Observations	12

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	42.84503	21.42252	138.9374	1.72E-07
Residual	9	1.387694	0.154188		
Total	11	44.23272			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	15.93659	0.842064	18.92563	1.48E-08
X Variable 1	-0.21416	0.020492	-10.4508	2.48E-06
X Variable 2	0.000899	0.000106	8.440559	1.44E-05

As indicated in Table 4.21, the R^2-value increased to 0.96, with a Confidence Interval variation of +/- 0.77 air voids. This is a significantly better fit than was seen in the overall model. This shows that the other control variables such as source, and gradation have an effect on the results. The effect may not be statistically significant, but it appears to be important from a practical application because of the air void limits used in practice. The fit of the model can be seen in Figure 4.12.

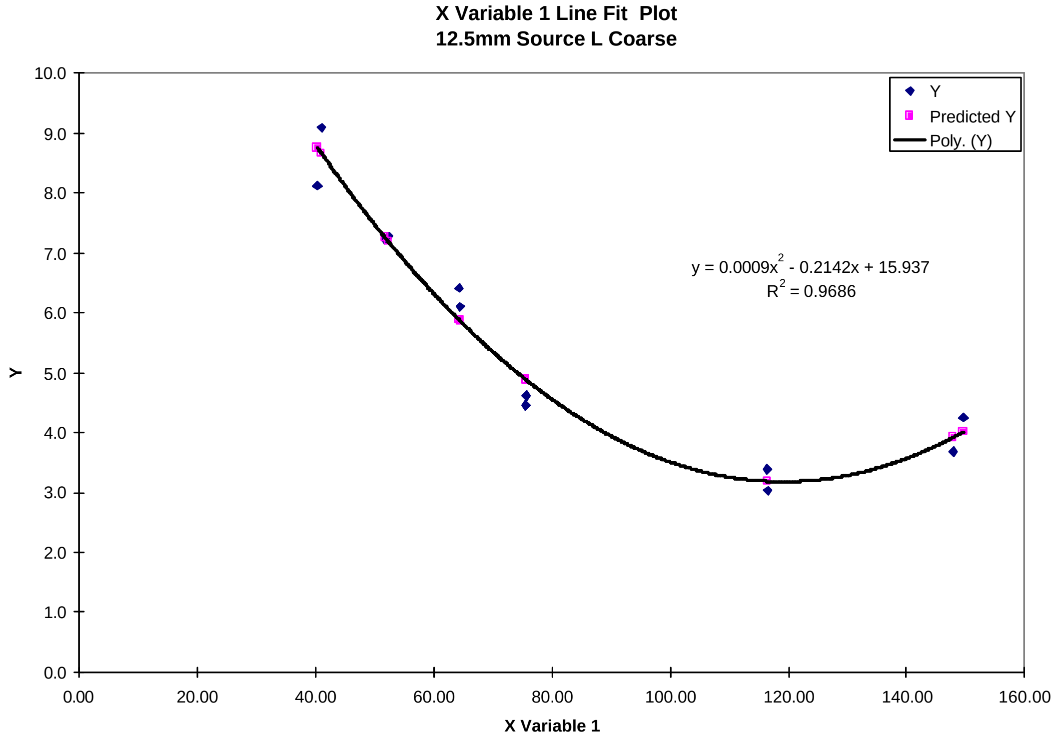


Figure 4.12. Regression Plot for 12.5mm Course Limestone, Source L

Using the results of this analysis, it can be determined that sample size has an effect on the density achieved. It can also be noted that mix characteristics like source properties, gradation and plant characteristics may also have an important effect on the density achieved; even if it the statistical analysis indicates that these factors are less important than the thickness to nominal maximum aggregate size ratio.

4.5.4 Number of Trials

In order to ensure that the statistical values obtained are valid, an analysis related to the number of trials must be conducted. Unfortunately, this type of analysis can not be conducted before the experiment, as the difference in means and the variance are not known. An equation provided by Nordheim and Clayton offers a method to determine this value (Nordheim and Delage. 1997).

$$n = 20*(\sigma^2/(\mu_2-\mu_1)^2) \qquad (4.1)$$

Where: n = number of samples required
σ^2 = sample variance
$(\mu_2-\mu_1)$ = difference in means

The difference in means $(\mu_2-\mu_1)$ in equation 4.1 in this experiment is the difference between the high and low level of the experiment. The variance and difference in means was calculated using the complete data set from the entire laboratory experiments, making the calculation representative of the experiment. The results used were the same ratios that were used for the statistical analysis.

Table 4.22. Number of Test Required for Meaningful Results

Response Variable	Average Diff. Between Ratios	σ^2	$n_{required}$	n_{actual}
Air Voids @ Ndes	0.71	0.16	7	43
Gyrations to 92%Gmm	1.74	1.19	8	30
CEI	2.15	1.83	8	36
CFI	1.77	1.44	9	36

Table 4.22 shows that the experiment included four times the number of tests needed to obtain statistically meaningful results, giving further credibility to the laboratory study.

4.6 EXTRACTION ANALYSIS

In order to ensure that crushing of the aggregates in the samples did not occur due to reduced sample size, extractions were run for all the sample sizes for Source L and for the 1,500 gram sample and the 4,700 gram sample for the other sources. By evaluating the thinnest sample and the standard sample size, the extreme differences in compaction size could be analyzed to determine the crushing effect. Extractions were run according to ASTM D 2172-95 (ASTM. 1996). All extraction results were analyzed for compliance to Wisconsin DOT Quality Control procedures.

Table 4.23 provides a summary of the gradation results from the extractions of the different sample sizes for the 19mm coarse limestone mixture from Source L, and how each sample compares to the job mix formula (JMF). All of the gradations were found to be similar to each other and the JMF. The largest difference on any sieve from the five extractions was 3.1%; as was seen on the 1.18mm (#16) sieve by the 1,500-gram and 4,700-gram samples. All samples tended to be finer than the JMF for sieve sizes smaller than the 4.75mm (#4) sieve. None of the differences between the JMF and the extraction results was more than 4%, which is within the allowable variation limits defined by WisDOT specifications; designed for uncompacted mixes (WisDOT, 2000). This indicates that crushing of the aggregates is not a significant factor for this mixture, regardless of specimen thickness.

Table 4.23. 19mm Coarse Limestone, Source L, Extraction Results

Specimen ID	**1500g**	**2000g**	**2500g**	**3000g**	**4700g**	
Sieve	%Pass	%Pass	%Pass	%Pass	%Pass	**JMF**
25	100.0	100.0	100.0	100.0	100.0	**100**
19	98.7	98.1	98.1	99.4	99.5	**98.2**
12.5	88.8	88.3	89.8	89.7	88.2	**88.8**
9.5	77.0	77.1	78.3	77.0	76.8	**76.4**
4.75	49.0	48.5	50.3	49.0	48.4	**46.5**
2.36	31.2	30.3	33.0	31.4	31.6	**29.3**
1.18	19.9	20.5	23.0	20.4	21.8	**18.7**
0.6	12.8	13.6	15.7	13.7	15.3	**11.8**
0.3	7.5	8.3	9.7	8.4	9.3	**6.3**
0.15	5.2	5.9	6.9	6.0	5.9	**4**
0.075	4.0	4.7	5.4	4.8	4.6	**3.7**

The same kind of results can also be seen in Table 4.24 for the 12.5mm coarse limestone mixture form Source L. For this analysis, the largest difference observed was 4.7% on the 12.5mm sieve between the 1,500 gram and 2,000 gram samples. In general, the samples tended to become finer than the JMF at the 9.5mm sieve. None of them however exhibited extreme behavior, and none differed from the JMF by more than 5%. In fact, with the exception of one result, all the results differed from the JMF by less than 3%.

Table 4.24. 12.5mm Coarse Limestone, Source L, Extraction Results

Specimen ID	**1500g**	**2000g**	**2500g**	**3000g**	**4700g**	
Sieve	%Pass	%Pass	%Pass	%Pass	%Pass	**JMF**
25	100.0	100.0	100.0	100.0	100.0	**100**
19	100.0	100.0	100.0	100.0	100.0	**100**
12.5	90.1	94.8	94.3	94.3	94.1	**95.2**
9.5	73.6	76.0	76.2	75.6	75.5	**74.8**
4.75	48.3	49.0	49.9	48.7	49.2	**46.9**
2.36	30.3	30.1	31.8	30.1	30.4	**28.4**
1.18	18.7	18.5	19.9	18.8	18.3	**17.5**
0.6	11.0	11.4	12.6	12.0	11.5	**10.8**
0.3	6.7	7.0	7.8	7.5	7.6	**6**
0.15	4.7	4.9	5.7	5.3	5.7	**4**
0.075	3.6	3.7	4.4	4.1	4.5	**3.2**

Table 4.25. 19mm Coarse Granite, Source M, Extraction Results

Specimen ID	**1500g**	**4700g**		
Sieve	%Pass	%Pass	**JMF**	**QC(1-1)**
25	100.0	100.0	**100**	**100**
19	98.5	98.1	**98.4**	**98.6**
12.5	79.1	75.6	**78.6**	**79.7**
9.5	65.3	64.3	**61.5**	**69.2**
4.75	43.6	41.4	**39.2**	**45.1**
2.36	31.0	29.8	**28.8**	**30.7**
1.18	23.2	22.1	**20.4**	**22.3**
0.6	17.0	15.3	**14.4**	**16.5**
0.3	10.8	9.5	**9.2**	**10.6**
0.15	6.9	6.7	**6.1**	**7.1**
0.075	5.3	5.2	**4.3**	**5.5**

Table 4.25 shows the results of the extractions from the 19mm coarse granite mix from Source M. The data results of this extraction indicate that the 1,500 gram sample is generally finer than the 4,700 gram sample, with the largest difference at 3.5% noted on the

12.5mm sieve for the 4,700 gram sample. The 1,500 gram sample more closely resembles the JMF and the Quality Control data from that date.

Table 4.26. 12.5mm Fine Gravel, Source K, Extraction Results

Specimen ID	**1500g**	**4700g**		
Sieve	%Pass	%Pass	**JMF**	**QC**
25	100.0	100.0	**100**	**100**
19	100.0	100.0	**100**	**100**
12.5	95.1	95.5	**97.3**	**97.1**
9.5	86.6	84.7	**89.4**	**88**
4.75	63.0	62.6	**66.3**	**66.3**
2.36	51.7	51.9	**55.2**	**54.7**
1.18	42.5	42.1	**44.2**	**44.8**
0.6	30.9	31.2	**30.5**	**31.7**
0.3	15.5	15.5	**14.2**	**14.2**
0.15	7.1	7.3	**6.9**	**6**
0.075	4.8	4.7	**4.6**	**4**

The same trend was noted for the fine gravel extraction samples depicted in Table 4.24. The largest difference between the two samples was 1.9% on the 9.5mm sieve. Both samples were generally coarser than the JMF and the QC data, but none differed from the JMF by more than 3.7%, which is noted on the 4.75mm (#4) sieve. The gradations do not become finer than the JMF or QC data until the 300-micron (#50) sieve.

The gradations of extracted samples indicate that no significant crushing occurs in the samples due to compaction in the gyratory compactor. All extracted samples were compacted to the N_{des} number of gyrations for that mix. Generally the highest changes in the gradation observed were approximately 9.5mm for the sieve, showing that there is some crushing of larger particles, but none more than 4%. The resulting change in the amount of material passing the #200 sieve was less than 2%. The extraction results for the rest of the mixtures, along with their plots are provided in Appendix D.

4.7 SUMMARY AND CONCLUSIONS OF THE LABORATORY STUDY

This chapter discussed the analysis of results from the laboratory compaction of 11 different Superpave asphalt mixes to N_{des} and N_{max}. Theses analyses were conducted for 5 different sample sizes ranging from 1,500 grams to 6,000 grams for each mixture. These samples were analyzed for their air voids, the number of gyrations needed to obtain 92% G_{mm}, and for their Construction Energy and Friction Indices (CEI and CFI). These analyses provided useful information about the results of compaction process of the materials in the SGC. The following are the primary findings resulting from these analyses.

1. Samples smaller than 3,000 grams resulted in higher air voids than those larger than 3,000 grams when compacted to N_{des} and N_{max} or higher. A negative trend between sample size and air voids was observed in the range from 1,500 grams to 3,000 grams, while a generally flat trend was noted from this point to the maximum sample size of 6,000 grams.
2. It was generally observed that the CEI and CFI values decreased with increasing sample size. There were a few cases where the 6,000-gram sample indicated an increase. It was noted that once in the 3,000-gram or larger range, the values of CEI and CFI did not vary significantly.
3. Using ratios to compare the different values for 1,500 gram, 3,000 gram, and 6,000 gram samples statistical analyses was performed. In each case, the ratio of 1500g/3000g to 6000g/3000g was significant, indicating that increasing and decreasing lift thickness would affect properties.
4. Gradation and nominal maximum aggregate size were significant only for limited combinations, particularly for CFI.

5. The source and type of the materials, number of ESAL's and replicate effects were not found to be significant for any combination.
6. The interactive effects that were most often observed to be significant were the effect of gradation and nominal maximum size, and the effect of gradation and source.
7. Extraction results showed that using different sample sizes had only minor effects on the gradation. The largest effect noted was a slight increase in the fineness of the gradation due to the compaction process.

Given the laboratory results, thinner lifts should provide more resistance to compaction and result in less density. It was found that the minimum lift thickness should range between 4 and 6 times the maximum aggregate size. Because of debates regarding whether SGC represents field compaction, it is important to note that the results of this analysis were based upon using the Superpave Gyratory Compactor. Confirmation of the laboratory results was verified with complimentary field analyses. The next chapter describes the field analysis and compares those results to the results of the laboratory study.

CHAPTER FIVE

FIELD STUDY

5.1 TESTING SETUP

Before finalizing the field study an extensive literature review was conducted to identify critical factors that should be included. One of the studies that was of special importance is the nuclear density study performed by Schmitt et al (1997) for WisDOT. A draft plan was prepared and presented to the Wisconsin Highway Research Program (WHRP) Flexible Pavement Technical Oversight Committee, which is comprised of representatives from WisDOT and industry. The members of this committee provided useful feedback and new information, which was necessary to develop the final field testing plan. The field study, which focused on measurements of density after compaction, included four field projects in which various combinations of mixture types and lift thicknesses were used.

The goal of each field study was to determine how lift thickness affects the final density of the pavement layer. A key element of this goal, an effort to obtain the thinnest layer allowed under the existing specifications. In addition, the field analysis also included efforts to try at least three different thicknesses to establish a density trend with the different thicknesses. Each project was selected for the field study consisted of at least a 1,500-foot strip at the pre-determined thickness, with at least 3 additional thicknesses to cover a range of thickness to maximum aggregate ratio.

The nuclear density gauge provides immediate and accurate density results in the field. Given that the majority of contractors and WisDOT use nuclear density gauges, their application in determining the pavement layer density for this project was appropriate.

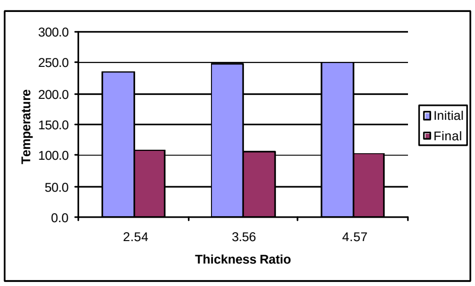
Nuclear density readings were taken after each roller pass in order to measure the changes in pavement density with each pass.

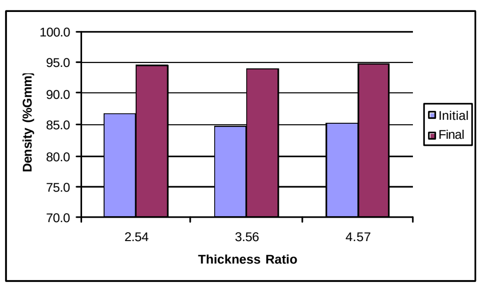
Two technicians from the University of Wisconsin-Madison were available to gather the nuclear density data from each field study. Since none of the technicians at the UW were certified to run nuclear density machines, Technicians from participating agencies ran the testing with the nuclear density machines. Technicians from the University worked collaboratively with each nuclear density technician to take the nuclear density readings after each roller pass; marking the point in the mat of each test in order to ensure repeatable and quality results. Standard state density procedures were followed to gather the data. The type of roller and number of passes was also recorded. Loose mixes were gathered from the field studies and compacted in the laboratory to provide the information used in the laboratory section of the report.

5.2 FIELD STUDIES

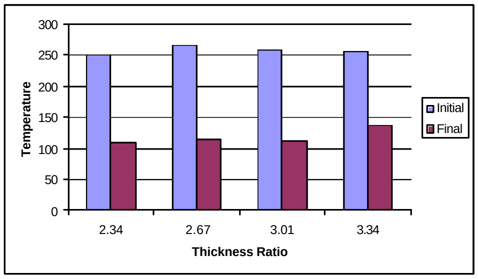
At the beginning of the field study it was clear that we needed to select the most critical factors that would affect compaction. It is well known that there are many factors that could affect achieving density among which mixture type, mixture temperature, lift thickness, and compaction effort (roller type and number of passes) are the most important. Since this was a comparative study in which same mixture will be used and same type of rollers would be used, these two factors were not considered. Lift thickness is a control factor and thus is automatically considered and controlled. Number of roller passes and temperature are therefore the remaining factors that need to be standardized so that the density results would not be confounded.

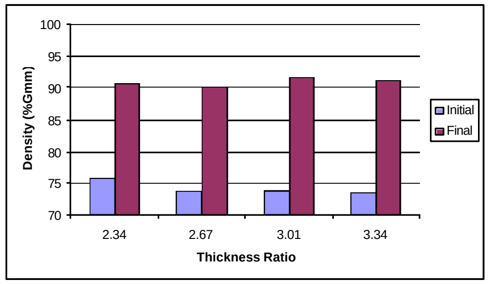
It was therefore decided that number of roller passes would be always counted and density measurements will be taken after certain levels of compaction based on the project rolling pattern and the timing. The need for temperature measurements was however debatable because it cannot be controlled and it could vary based on weather conditions. It was therefore decided to measure it in certain project and monitor its variation before including in the analysis. Figure 5.1 shows examples of the data for 2 of the projects during which the temperature was monitored continuously. As shown, the variation was not found to be significant and also there was hardly any trend that could be found in relation to lift thickness or density. It was therefore decided not to continue recording temperature but make sure no density is taken when significant variation in temperature is suspected or observed in the projects. No incident in any of the remaining projects required such an action. The complete set of temperature data is shown in Appendix E. In the following sections density data analysis is conducted without referring to temperature because it was not believed to play a role in comparing density within each project for each mixture.





a) Temperature and Density Measurements for Project (Main St.)





b) Temperature and Density Measurements for Project (STH 13)

Figure 5.0 Temperature and Density of Asphalt Mixtures Measured in the Field

5.2.1 Field Study K, CTH "VV", Summer/Fall 2000

The first field study was conducted in the late summer/early fall of 2000. The project site was located along a stretch of County Trunk Highway VV, and consisted of a fine graded 19mm crushed gravel mixture for the binder course, with a 12.5mm fine graded crushed gravel mixture for the surface course. WisDOT classifies both mixtures as E3. The project was constructed on a fresh gravel base.

Table 5.1. Project K, CTH "VV" Test Sections

Mix	Thickness	Ratio	Mix	Thickness	Ratio
Binder	1.5"	2	Surface	1.25"	2.5
Binder	2.0"	2.7	Surface	1.75"	3.5
Binder	3.5"	4.7	Surface	2.25"	4.5
Binder	4.5"	6	Surface	3.0"	6

As part of this project the research team analyzed four different lift thicknesses for each mixture; with the characteristics depicted in Table 5.1. The ratios of lift thickness to nominal maximum aggregate size are also provided. The first two binder ratios and the first surface ratio are thinner than current WisDOT specifications. The binder test sections and the 3” surface section were paved on August 23, 2000. The weather was sunny with a high temperature of 78° F on that day. Pneumatic tire, vibratory, and static rollers performed compaction on the project.

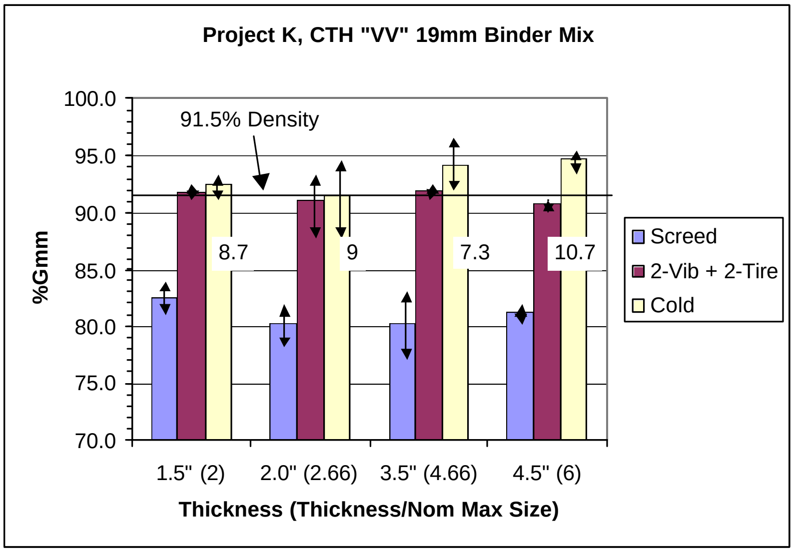


Figure 5.1. Project K, 19mm Binder Density Results

The results of the binder part of Project K are shown in Figure 5.1. During the paving of the project, the vibratory and pneumatic tire rollers took turns going over the same points, so the most accurate way to present the results was to look at a representative number of passes. In figure 5.1, the blue (or first) bar for each lift represents the density after the screed. The maroon (or second) bar represents the density after two vibratory passes and two pneumatic roller passes. The yellow (or third) bar represents the final density after the cold roller has finished rolling the section, and the number displayed on that bar is the average number of roller passes used in that section to get the final density result. The double-ended arrows represent the range of results gathered in the three data points that made up the measurement. In Table 5.2, the average results represented by the bars are shown.

Table 5.2. Project K, 19mm Binder Density Averages

Lift	Screed	2-Vib + 2Rub Tire	Final	Passes to 91.5%
1.5" (2)	82.5	91.8	92.5	6.0
2.0" (2.66)	80.3	91.0	91.6	6.3
3.5" (4.66)	80.3	91.9	94.2	4.3
4.5" (6)	81.4	90.8	94.7	7.3

The results show that the two thicker layers, with ratios above the State's specified lift thickness specification provide the best density results. The thinner lifts achieve the 91.5% target density. The number of passes to reach 91.5% density varies, but generally it is in the 6 to 7 range, with the 3.5" lift reaching the target in only 4 passes. One of the troubling facts about this study is that the range in values is great, especially for the middle two test samples. Quality Control results indicate that the air voids increased in the mix throughout the day. The fact that the thinner layers were paved later in the day could explain the lower voids that observed in those layers. Overall, the thinner layers had about 2% more air voids than the thicker layers. Thinner layers with increased air voids matches the laboratory findings, with about a two percent shift in density from a ratio of 2 to the optimal specimen size.

The second phase of the project was conducted on October 2, 2000 when three thinner layers for the surface mixture were paved using only vibratory and static rollers. The weather was sunny with a high temperature of 70° F.

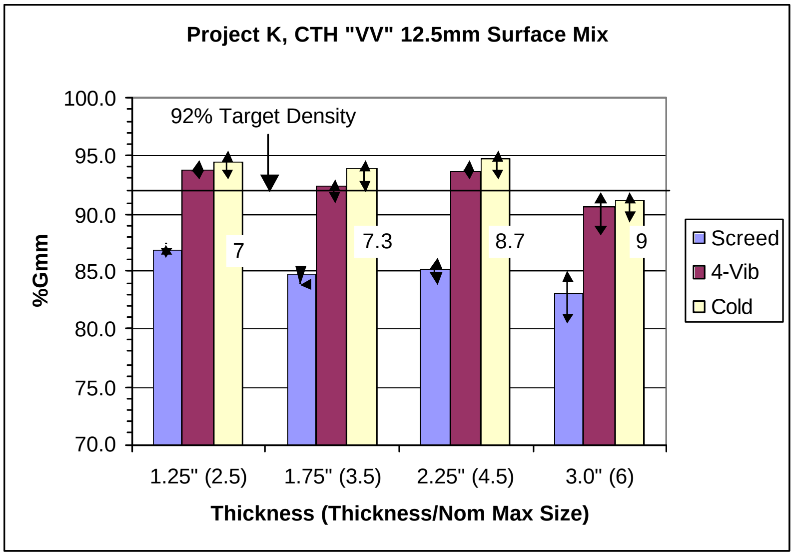


Figure 5.2. Project K, 12.5mm Surface Density Results

The data for this project is plotted in the same manner as the previous one, except that this time the intermediate density is representative of four passes of the vibratory roller. As depicted in Table 5.3, the densities for the three thinner lifts are all about the same.

Table 5.3. Project K, 12.5mm Surface Density Averages

LT	Screed	4-Vib	Final	Passes to 92%
1.25" (2.5)	86.8	93.8	94.5	1.7
1.75" (3.5)	84.7	92.3	93.9	2.3
2.25" (4.5)	85.2	93.6	94.7	2.3
3.0" (6)	83.2	90.6	91.2	8.3

The results show that the target density was easy to achieve for the three thinner lifts, but was not achieved for the 3" lift. For the purposes of this project, the 3" lift for this project can best be described as an outlier. The 3' lift was compacted August 2000 with the binder lifts for the project, which means that the pneumatic tire roller was involved in the process. QC data from that date also indicates that the mix had 7% air voids in the lab; 3% above the target. Combining both factors means that the thicker section can not be compared with the thinner thicknesses, which had QC values of 4% air voids.

Overall, the surface lift showed no effect of lift thickness on density, with a maximum variation of 0.8% in the final density. The number of roller passes was consistent throughout the process, with 92% density being reached at two roller passes. The lack of change in density seen in the field does not match the results of the laboratory mix compaction. At a ratio of 3 in the lab, the mix had 2.5% higher air voids than the sample at a ratio of 6. This trend is also contrary to what was seen in the compaction of the binder mixtures for this project.

5.2.2 Field Study M, STH 13, June/July 2001

Field Study M was a completely different from Field Study K. In Project M, crushed granite was used to produce the mixtures instead of crushed gravel. The project used E10 mixes, with a coarse 19mm binder course and a fine 12.5mm surface course. The base of the project area was a milled asphalt surface. The project consisted of four different binder thicknesses and four different surface thicknesses, which can be seen in Table 5.4. The project was conducted in the early summer of 2001.

Table 5.4. Project M, STH 13 Test Sections

Mix	Thickness	Ratio	Mix	Thickness	Ratio
Binder	1.75"	2.3	Surface	1.5"	3
Binder	2.0"	2.7	Surface	1.75"	3.5
Binder	2.25"	3	Surface	2.0"	4
Binder	2.5"	3.3	Surface	2.25"	4.5

The ratios used in this project were clustered towards the thinner State specifications, with the first three binder ratios and the first two surface layers as thin as or thinner than the current WisDOT specification for minimum lift thickness.

The first day of paving for the Project M was on June 25, 2001. All four of the binder lifts were paved that day. The roller pattern on this project consisted of two tire rollers in the breakdown position, followed by vibratory and static rollers. The weather on the 25th was sunny with a high of 90° F.

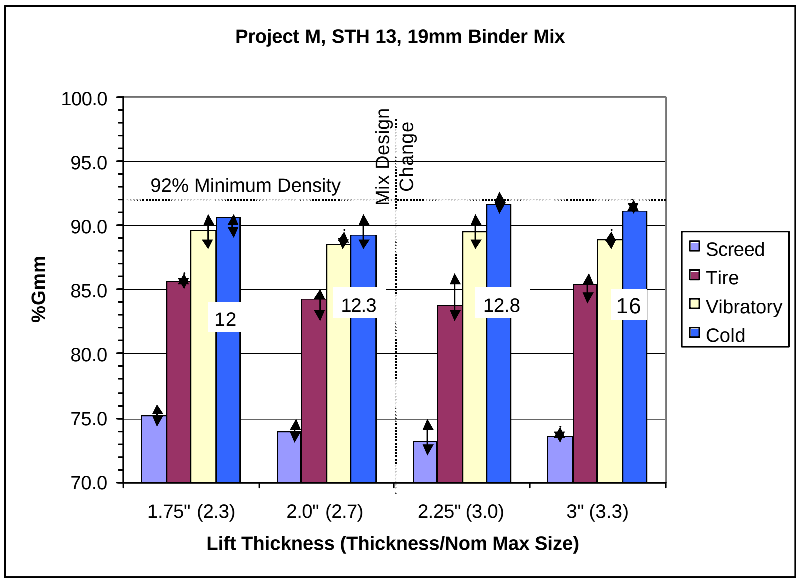


Figure 5.3. Project M, 19mm Binder Density Results

The results depicted in Figure 5.3 are similar to those seen for Field Study K, but the results plotted this time are after the screed, tire rollers, vibratory rollers and cold rollers respectively, rather than in the middle of them as was done for Field Study K. The numbers on the cold roller bar represent the total number of passes to achieve the final density.

Table 5.5. Project M, 19mm Binder Density Averages

Thickness	Screed	Tire Rolling	Vibratory Rolling	Cold Rolling
1.75" (2.3)	75.2	85.7	89.6	90.6
2.0" (2.7)	74.0	84.3	88.6	89.3
2.25" (3)	73.2	83.9	89.6	91.7
2.5" (3.3)	73.5	85.4	88.9	91.2

The average results are shown in Table 5.5, which shows densities lower than expected. First, none of the test sections reached the target density, suggesting that the lift thicknesses were too thin. More significant was the mix design change made between the 2.25" and the 2" sections. The mixes used in the 2.5" and 2.25" sections had QC data low in air voids; at about 3%. The QC for the mix used for the thinner section had air voids around 4%; a 1% shift in the density that could make the results between the lifts equal. The thickest lift also had four more roller passes than the remaining layers. The laboratory compactions of this mix had a 3% shift from the thinner lifts with a ratio of about 2.1 to the standard size specimen with a ratio of 6, and a 1.8% density shift between ratios of 2.1 to 2.9. These results match the data shown here, if the mix change and the change in air voids are not taken into account. However, a change in the job mix formula, results in a less clear match between the lab and the field results.

The surface layers were paved on July 6th, another warm and sunny day with highs in the 90's and high humidity. A similar roller pattern used for the binder lift was used for this project. Three density technicians from WisDOT gathered the nuclear density data. The results of the project are displayed in Figure 5.4.

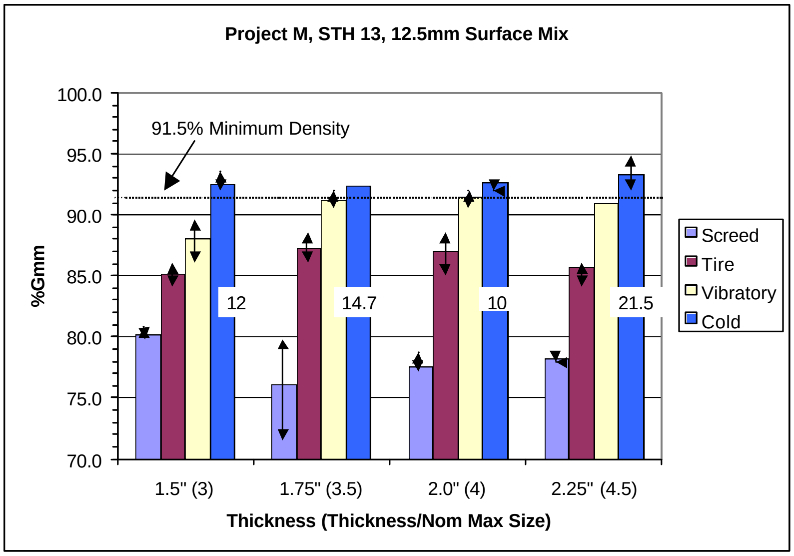


Figure 5.4. Project M, 12.5mm Surface Density Results

Table 5.6 Project M, 12.5mm Surface Density Averages

Thickness	Screed	Tire Rolling	Vibratory Rolling	Cold Rolling
1.5" (3)	80.2	85.2	88.1	92.6
1.75" (3.5)	76.0	87.2	91.2	92.4
2.0" (4)	77.6	87.0	91.5	92.6
2.25" (4.5)	78.3	85.7	91.0	93.3

The results for the surface lifts indicate that there was no significant difference in the densities due to the different lift thicknesses. A significantly higher number of roller passes was used to compact the 2.25” lift. The rest of the lifts are in the same range for density and for the amount of compactive effort applied. The laboratory showed a 1.5% air void shift for the difference between ratios of 3 to 4, where the field showed the same density. QC data for the project indicated low air voids for the mix with an average of 3.3%.

For both phases of the project, the various nuclear density machines used were correlated by having both of them read all of the final density readings over the same point and in the same position. Adjustment factors were developed from these readings to correlate the data to each other.

Overall, this project showed that the different thicknesses had little effect on density if mixture differences were taken into account. It also showed that the field and the laboratory results did not have a direct correlation; as thinner lifts in the field did not demonstrate the same behavior that was seen in the lab.

5.2.3 Field Study N, IH 43, June/August 2001

Field Study N consisted of testing an E10 binder mix overlaid on an Interstate Highway. The mixture tested was a fine graded crushed limestone mixture, with four different thicknesses tested on two different dates during the summer of 2001.

Table 5.7. Project N, IH-43 Test Sections

Mix	Thickness	Ratio
Binder	1.5"	2
Binder	2.0"	2.7
Binder	2.25"	3
Binder	2.5"	3.3

Table 5.7 shows the four different sections tested during Field Study N. The first two sections were paved on June 27, 2001. The contractor used a vibratory roller in the breakdown position, followed by the pneumatic tire roller and the static roller. The weather was 80° F and sunny. WisDOT and the contractor provided nuclear density technicians. The remaining two lifts were paved on August 27, 2001, an overcast day with a high temperature

of 75° F. WisDOT provided two nuclear density technicians. The same roller pattern was used.

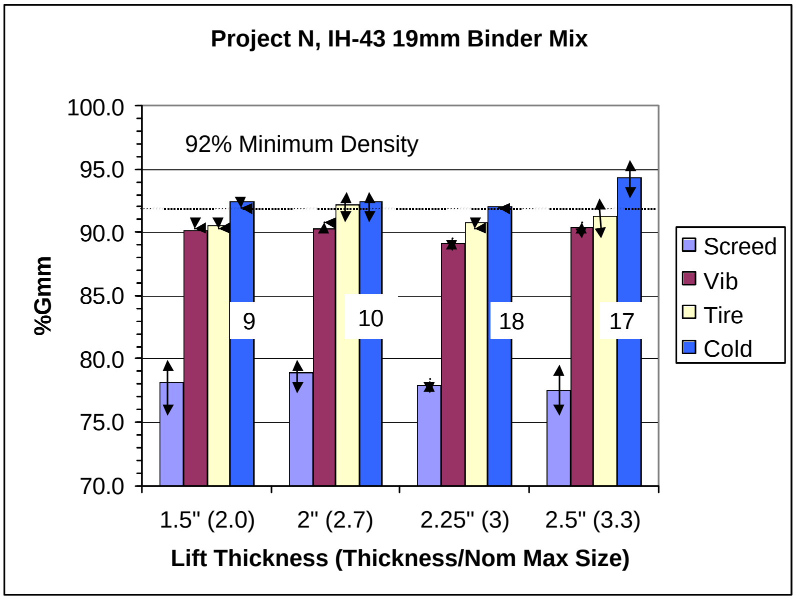


Figure 5.5. Project N, 19mm Binder Density Results

Table 5.8. Project N, 19mm Binder Density Averages

Thickness	Screed	Vibratory Rolling	Tire Rolling	Cold Rolling	Passes to 92%
1.5" (2.0)	78.1	90.2	90.6	92.5	9
2" (2.7)	79.0	90.3	92.2	92.4	7.7
2.25" (3)	77.9	89.2	90.8	92.1	18.0
2.5" (3.3)	77.5	90.4	91.3	94.4	17.3

The results of the tests are provided in Figure 5.5 and Table 5.8. Even though the thickest layer achieved higher density than the thinner layers, the two thicker layers received 7 to 8 more roller passes than the thinner lifts. All of the lifts achieved the target density of 92%, with the thinner lifts achieving this density with about 7 to 8 less roller passes than the thicker lifts. QC data from the first day of paving on the 2.25" and 2" sections had lower air voids than normal, with a value of 3.4%. On the second day, QC results showed air voids around the target of 4%. The nuclear density machines were correlated at the end of each day.

In the lab, changing ratios from 2 to 2.5 resulted in a 2% drop in voids. In the field, the change did not result in a change in density.

5.2.4 Field Study P: CTH "H", September 2001

The fourth and final field study of the project consisted of testing E3 binder and surface courses on a pulverized asphalt base. Both the surface and binder layers were made from fine graded crushed limestone mixtures of 12.5mm and 19mm, respectively. Three binder lifts and three surface lifts were paved in September of 2001. The three thicknesses tested are depicted Table 5.9.

Table 5.9. Project P, CTH "H" Test Sections

Mix	Thickness	Ratio	Mix	Thickness	Ratio
Binder	2.5"	3.3	Surface	1.25"	2.5
Binder	3"	4	Surface	1.5"	3
Binder	3.25"	4.3	Surface	2"	4

The binder test sections were not as thin as those tested in the previous studies, but the surface test sections included a section with a ratio of 2.5, which is similar to those seen in the previous studies. The contractor used a vibratory roller for the breakdown and densification parts of the process, followed by a static roller to finish the mix. One nuclear density machine was provided by the contractor and one by WisDOT. The first day of paving was on September 4, 2001, with the three binder lifts paved on that day. The weather was sunny, with a high temperature of about 70° F.

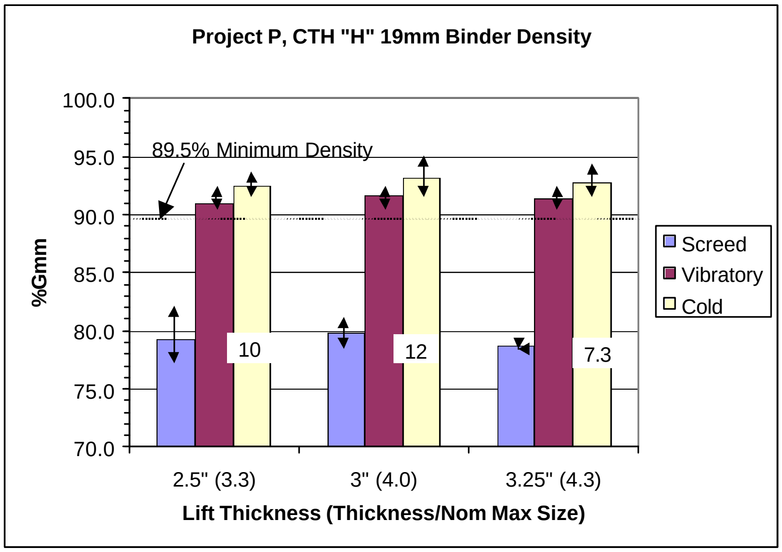


Figure 5.6. Project P, CTH "H", 19mm Binder Density Results

Table 5.10. Project P, CTH "H", 19mm Binder Density Averages

Thickness	Screed	Vibratory	Cold	Passes to 89.5%
2.5" (3.3)	79.3	91.0	92.5	2.5
3" (4.0)	79.8	91.6	93.1	2.8
3.25" (4.3)	78.7	91.4	92.7	2.3

As depicted in Figure 5.7 and Table 5.10, it was observed that there was essentially no difference in density due to changing lift thickness. The number of passes necessary to achieve the target density of 89.5% is also about the same. The density shift of about a 1.5% decrease observed in the lab resulted from a change in ratio from 3 to 4, which is three times that which was noted in the field for the same mixture. Density gauges were correlated at the end of the day.

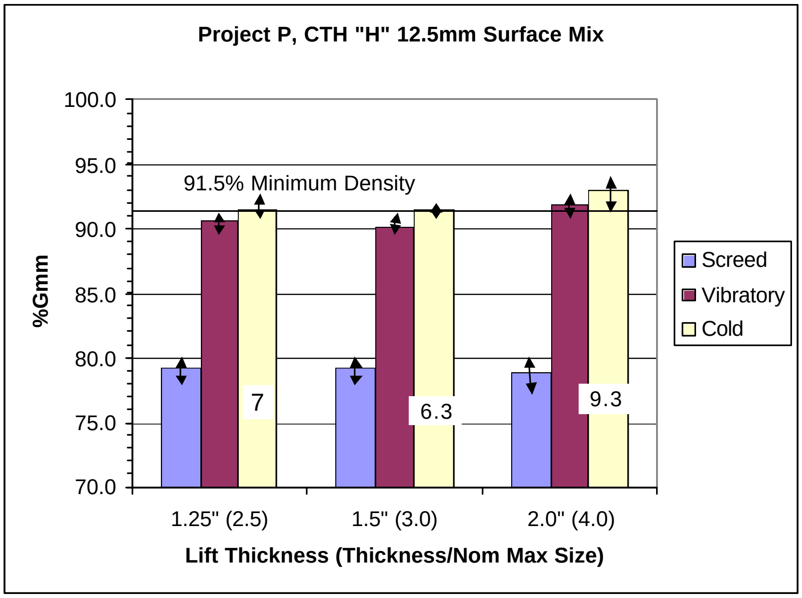


Figure 5.7. Project P, CTH "H" 12.5mm Surface Density Results

Table 5.11. Project P, CTH "H" 12.5mm Surface Density Averages

Thickness	Screed	Vibratory	Cold	Passes to 91.5%
1.25" (2.5)	79.2	90.6	91.6	5.0
1.5" (3.0)	79.3	90.1	91.5	4.8
2.0" (4.0)	78.9	91.9	93.0	5.3

The results of the surface study for Project P, shown in Figure 5.7 and Table 5.11, demonstrate similar trends seen previously; with no real change in density due to a change in thickness. The thicker lift (2") had a higher density by 1.5%, which was more attributed to an increase in the number of roller passes compared to passes on the other sections. QC for the day noted air voids close to 4% throughout the day. The number of passes to achieve the target density for all lifts is approximately 5. Density gauges were correlated at the end of the day. Weather for the day was windy, with a high temperature in the 60's.

The change in air voids in the laboratory due to a change in thickness to nominal maximum aggregate size ratio from 3 to 4 was about 2%, which is similar to what was observed in the field. In the field, however, the 2” section was subjected to three additional passes (50% more roller passes) compared to the 1.5” section. It could therefore be concluded that the field trends do not match the laboratory trends. This further confirms the difference in results that were seen between the lab and field on previous projects.

The analysis of data collected during the field study shows that there was no significant change in density due to changes in lift thickness. The study also shows that there is a discrepancy between the asphalt mixtures in the lab when compared to the field. To see if the changes in density due to the change in thickness were significant or not, statistical analysis of the data was conducted. Complete data tables for each of the projects is provided in Appendix F.

5.3 STATISTICAL ANLAYSIS OF THE FIELD STUDIES

Statistical analyses conducted during the field study were similar to the analytical processes completed during the laboratory analysis. The ANOVA analysis was performed, looking at the response of certain dependant variables based on the different levels of the independent variables.

Table 5.12. Experimental Setup for the Field Studies

	Material Type	Crushed Stone				Gravel			
	Gradation Type	Coarse		Fine		Coarse		Fine	
	Nom. Max. Size	19mm	12.5mm	19mm	12.5mm	19mm	12.5mm	19mm	12.5mm
Source	K							E3	E3
	M	E10			E10				
	N			E10					
	P			E3	E3				

Table 5.12 provides a summary of the setup for the experiment. The E3's or E10's represent the traffic design of the mixes. Since Source L was only tested in the laboratory it was removed from the field study table. Given that each project had three to four different thicknesses, a table like this was not used to organize the data.

Table 5.13. Variable Setup for Field Studies

	Control Variables	Level 1	Level 2	Response Variables
1	Gradation (G)	Coarse	Fine	Density
2	Layer (L)	Binder (19mm)	Surface (12.5mm)	Roller Passes to 92%
3	Ratio (R)	Continuous		
4	Mix Type (M)	E3	E10	
5	Project (P)	Four Levels: K, M, N, P		
6	Run (N)	Four Replicates		

Table 5.13 shows the different variables studied during the field experiment. This is similar to the format of the laboratory study, with two exceptions. For this portion of the study, the control variable ratio (R) was a continuous variable, as different ratios were looked at in each project. The source variable (P) was considered at four levels representing the four different projects. The control variable run (N) for the field study contained as many as four replicates, while the laboratory included only two. Each run represented one density data point used to calculate the averages in the field result figures shown in the previous section.

Table 5.14. Full Analysis of Density Variation from Field Measurements

Source of Variation	*DF*	*Sum of Square*	*Mean Square*	*F-Value*	*Sig. Level*
Main Effects					
Layer (L)	1	25.03	25.03	14.21	0.0003
Ratio (R)	1	0.60	0.60	0.34	0.56
Project (P)	3	47.93	15.98	9.07	<.0001
Run (N)	3	5.13	1.71	0.97	0.41
Interactive Effects					
Ratio*Layer (R*L)	1	23.95	23.95	13.6	0.0004
					R^2 = 0.4389

The results of the field study statistical analysis for the effect of the independent variables on field density are provided in Table 5.14. As noted, the results show that the Project (P) and Layer (L) factors have a fairly significant effect on the density achieved. The interactive effect of Ratio and Layer (R*L) is important. Although this model shows that these factors are significant, the R^2 of the model is low, with a value less than 0.50. This indicates that other factors could be attributed to the density shifts that were not considered in the model.

Table 5.15. Individual Project Statistical Analysis for Density Achieved

	Project			
	Project K	*Project M*	*Project N*	*Project P*
Main Effects				
Layer (L)	0.02	N	N	N
Ratio (R)	N	N	N	N
Project (P)	N	N	N	N
Run (N)	N	N	N	0.05
Interactive Effect				
Ratio*Layer (R*L)	0.02	N	N	N
Layer*Run (L*N)	N	N	N	N
Ratio*Run (R*N)	N	N	N	N
R^2	0.3821	0.3218	0.7322	0.4328

N= Not Significant

Table 5.15 provides the results of the statistical analysis of each individual project. By analyzing each project individually, it can be seen that the ratio of lift thickness to nominal maximum aggregate size (R) is not significant for any of the projects. The layer type was found to be significant for the Field Study K, and the replicate effect was significant for Field Study P. The interactive effect of Ratio with Layer was significant in Field Study K, where just the layer effect was significant. All other interactive effects were insignificant for the remaining projects. The R^2-values for three of the individual projects were low (less than 0.50), and the interactive effects could not result in acceptable R^2 value. Only Project N provided a significant R^2, but none of the independent variables showed a significant effect.

Table 5.16 Number of Tests Needed for Statistically Significant Results

Response Variable	*Average Diff. In Density*	*Variance*	$n_{required}$	n_{actual}
Density				
Full Model	2.08	2.78	13	80
Project K	2.08	3.93	18	24
Project M	2.08	1.55	7	22
Project N	2.08	1.48	7	11
Project P	2.08	0.83	4	23

Table 5.16 shows the results from Equation 4.1, used to determine an adequate number of tests for meaningful results. The results indicate that by looking at the research project as a whole, there were enough data points for density to ensure statistically meaningful results, as noted in the full model results.

5.4 LAB AND FIELD CORRELATION

It was clearly observed during the lab tests, that thickness of the compacted samples had a significant effect on the percentage of air voids, with the thinner, 1,500-gram samples having as much as 5% more air voids when compared with the 3,000-gram samples or the standard 4,700-gram samples. In the field, however, densities varied by only as much as 2% due to thickness, with the majority of variations due to the change in the number of roller passes or changes in the mixture between measurements.

To understand the effects on density variations by other causes, the location of the specimen in the mold, and the rigidity of mold were considered further. The effect of both of these aspects were looked at in the compaction process to see how much, if any, effect they had on the densification process of the “thin lift” specimens.

Previous research by Hall, et al, also showed an effect of specimen height in the compaction process. Their results noted that a change in specimen size would result in a 2-3% shift in the air voids (Hall et al. 1997). A study by Jonsson demonstrated that a change in height by 20% could result in a change in density (Jonsson 2001). Both of these studies, along with the experience of other asphalt experts indicated that lower densities are measured in thin samples in the SGC. Two possibilities might explain this behavior. First, the mold base of the SGC was too rigid and as a result, did not simulate underlying layers of pavements in the field. The second possibility was that the position of the sample in the mold relative to the compaction ram resulted in the variation.

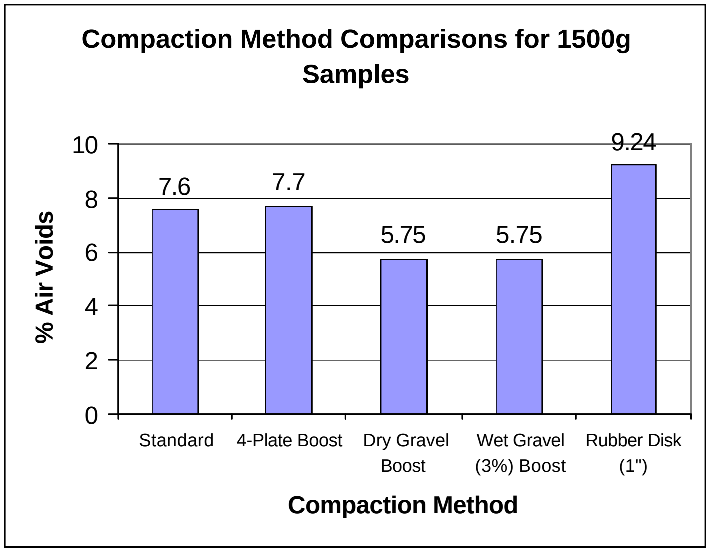


Figure 5.8. Results of Compaction Method Study in the Lab

To examine these possibilities, compaction under different conditions was repeated in the lab using the SGC. The results of this analysis are provided in Figure 5.8. The same loose mix collected from the surface of Field Study P, a 12.5mm fine limestone blend, was used for each of the mixes tested. All samples were 1,500 grams in size, and all were compacted to N_{des}, 75 gyrations. The results indicated are from the average of at least two specimens. The standard compaction method is demonstrated in the first bar, with voids of 7.6%, which is 3.5% higher than the results observed using the standard compaction height.

In order to make sure that this difference was not due to the location in the mold relative to the compaction head of the SGC, four top plates from the compactor were placed under the sample, and then compacted. This increased the height by 40mm, resulting in a height slightly higher than the 3,000-gram samples, which had lower air voids for the same compactive effort. These results show that the change in height had no major effect on the densification of the compacted sample, with a change of only 0.1% in density. This eliminated the idea that the location of the sample in the mold was responsible for the change in density.

The next step was to look at the effect of the rigidity of the mold. Since the mold is made of stainless steel, it was surmised that the inflexibility could be a factor in the compaction process. In order to test this concept, the samples were compacted on two different base materials; one an aggregate base with an aggregate gradation equal to that of a Grade 3 base course, and the other of silicone rubber with a hardness equal to that of the average tennis shoe.

The gravel bases were tested under two conditions, completely dry and moistened with 3% water. Efforts to compact the gravel bases to 95% of the dry density was difficult, but 84% was reached using the gyratory compactor and determined to be a sufficient stable base for compaction. The asphalt specimens were similarly compacted and resulted in a 2% decrease in voids. This significant jump appears to prove that the hardness of the metal was a serious barrier in getting the laboratory compactions to equal the compactions experienced in the field. Then the material was tested on four silicone rubber disks, with a durometer value of 70. The result was a 1.5% increase in voids, or a loss in densification. The results from this analysis indicate that the base material used must be similar to the field conditions.

Table 5.17. Compactive Resistance of Test Specimens

	Work (Kpa)	CEI	CFI
4-Plate	16.7	591.7	1156.7
Rubber	21.8	651.9	1695.5
Gravel	41.8	507.9	1962.9

Table 5.17 shows the average results gathered from the GLPA and the densification curve. The compaction work on the materials more than doubled with the gravel base, compared to the standard compaction method. The CEI's decreased slightly with the change in base materials, and the CFI's almost doubled with the use of the aggregate base. The decrease in CEI was expected, but the increase in CFI was a surprise. This was contrary to the trends seen the rest of the test samples, and in other research with the GLPA.

5.5 Finite Element Analysis

To explain the effect of sample size on the densification process in the SGC finite element analysis was used to estimate the distribution of stresses and strains in the sample using the boundary conditions that best simulate the SGC. By running a finite element analysis using the ANSYS/Structural program, the internal forces that the sample is undergoing during the compaction processes can be modeled and estimated.

In order to do this, the properties of the materials being worked with need to be determined. In Table 5.18, the properties that were used in this modeling process are listed. These values were consistently used in the modeling process in order to allow for comparison of the models.

Table 5.18. Material Properties for Finite Element Analysis

Element	Value
Mold (Side & Bottom) Compactive Force	Perfectly Rigid 600 KPa
Asphalt Modulus	500 KPa
Aggregate Base Modulus Angle of Gyration	200,000 KPa 1.25 Degrees

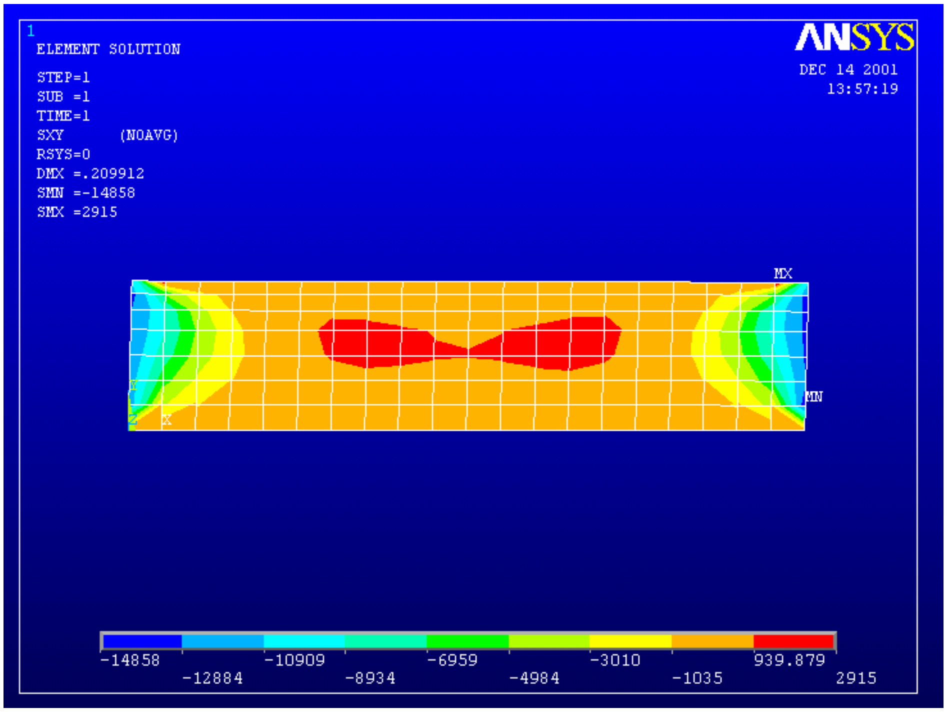


Figure 5.9. ANSYS Analysis of 1500 gram Sample

In Figure 5.9, a 1500 gram sample compacted on the rigid base material is shown. In Figure 5.10, a 3000 gram sample is shown. The results of this analysis do not explain the cause of the differences but it does indicate that the stress distribution is affected by the sample size. Both the magnitude of the shear stresses (as shown by the different shades of color) and the distribution, as shown by the area boundaries are very different. It therefore may be inferred that the differences are caused by different distribution of stresses in the molds. Looking at the 3000 gram sample in Figure 5.10 shows a large region of shear in the opposite direction that is seen in the rest of the sample in the center. The opposite shear can be seen in 52 of the 220 (24%) elements. The maximum shear values can still be seen on the outside edges of the samples. With this shown, the argument that the opposite shear direction in the center of the sample provides resistance to compaction is eliminated, as the 3,000 gram samples typically had no problems with the densification process.

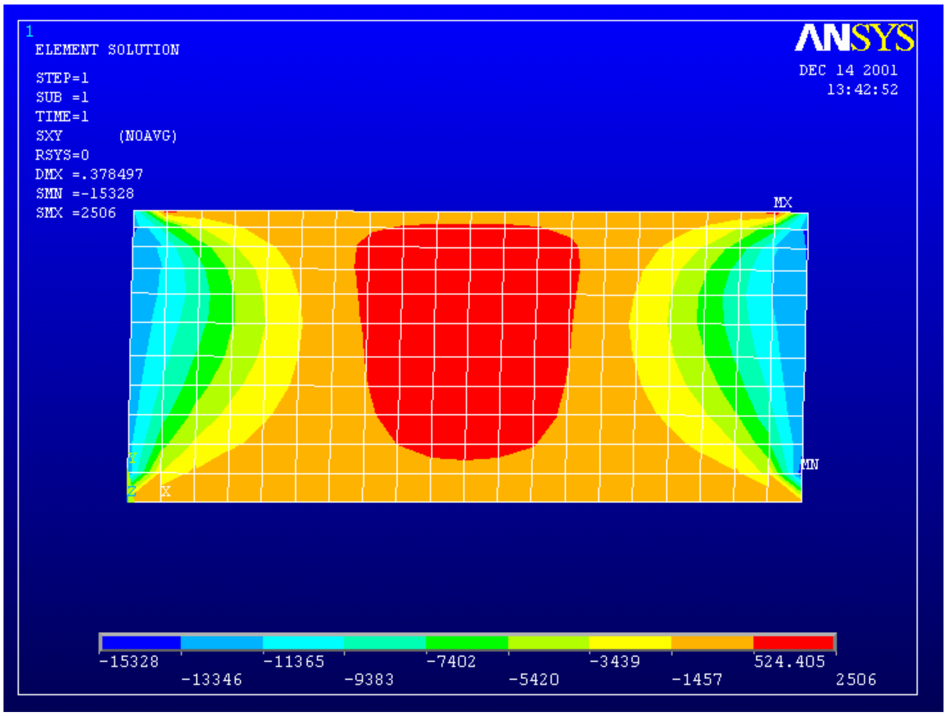


Figure 5.10. ANSYS Analysis of 3000 gram sample

Since it was previously seen that compaction on aggregate bases reduced the air void content, finite element analysis of compaction of a 1,500 gram sample on an aggregate base was conducted to determine what occurs when changing the base materials. It can be seen in

Figure 5.11 that the largest values are still at the edges, but this time, the larger values reach further into the middle of the sample when compared to the 1500 gram on solid base. It was also noted that there is not any shear that is occurring in the opposite direction in the center of the sample. This demonstrates that the aggregate base can have an effect on the internal forces occurring within an asphalt sample during compaction.

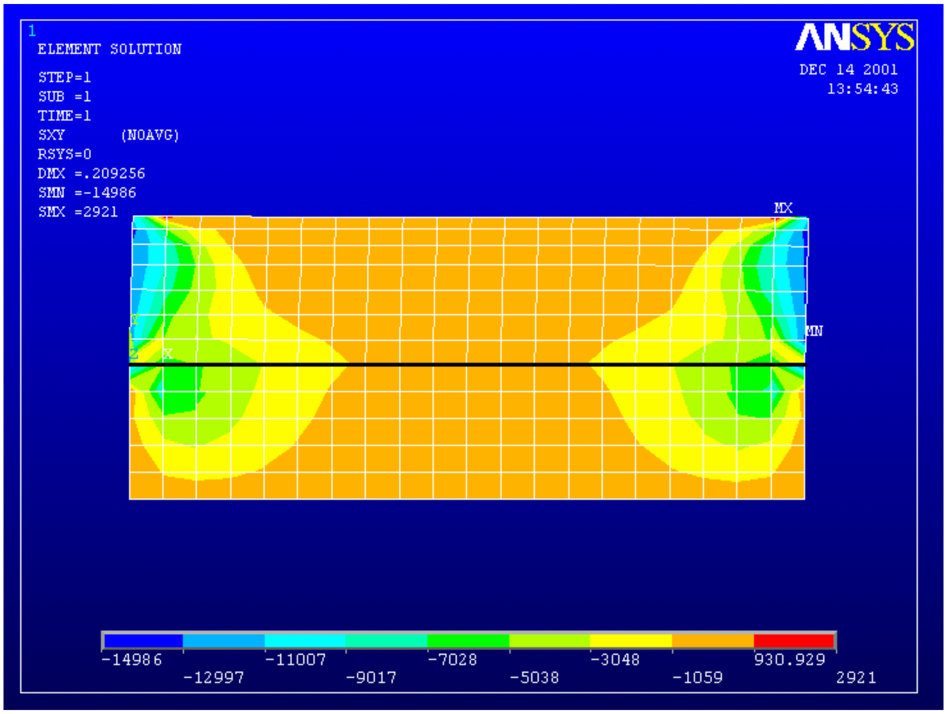


Figure 5.11. ANSYS Analysis of 1500 gram Sample on Aggregate Base

This short analysis using finite element is a starting point for future work to explain the effect of sample size. It is important that this work continue because just knowing that lift thickness or sample size has an effect is not sufficient, it requires a clear engineering explanation.

The results of this testing were not meant to develop any one conclusive procedure to modify the current compaction process being used to evaluate lift thickness. What it does demonstrate, however, is that compacting specimens on a softer base is more representative of how the material is compacted in the field. This represents a possible method to evaluate the difficulty in compacting the material in the field at thin lifts.

5.6 SUMMARY OF FINDINGS

Measurements of density after compaction were collected on four field projects in which various combinations of mixture types and lift thicknesses were used. The following are the main findings drawn from the field data.

1. There are many factors that can affect the densification process of asphalt mixes in the field, other than the roller types and rolling pattern. Temperature, climate, changes in mix design as witnessed in the quality control data, and changing voids in the mix are factors that can have just as much of an effect on density as the specifics of the rolling process.
2. The change in lift thickness was not found to have a significant effect on the final density for a given number of roller passes. All of the projects generally had the same density throughout the project, except for a few cases where other factors played a role, such as changing mixture characteristics.
3. It was commonly observed that the number of roller passes to achieve the target density increased with thickness, which contradicts what was seen in the lab; that thin lifts required more compaction.

4. Statistical analysis indicates that, the thickness to nominal maximum size ratio did not have an effect on the density achieved. With this said, it should be noted that the model coefficient of determination (R^2) was low, which indicates that there could be other factors, not included in the model, that play a role.
5. The field measurements do not conform to the trends observed in the lab, which show that sample thickness is an important factor controlling density. In fact, field results show that thicker lifts generally require more compactive effort.
6. There is no basis to believe that thin lifts (in the range covered in this study) would result in lower densities compared to thick lifts.
7. The correlation between the laboratory and the field was less than expected. One of the possible reasons for this is the rigidity of the SGC mold base. Compaction of mixes on aggregate bases reduced the air voids on average by 2%.

CHAPTER SIX

SUMMARY OF FINDINGS AND CONCLUSIONS

6.1 SUMMARY OF FINDINGS

This project included a laboratory study phase and a field study phase. In each phase a set of mixtures were compacted at varying lift thickness values that were selected to cover the range of thickness to maximum aggregate size ratios used in practice. The main objective was to evaluate the effect of this ratio on achieving density in the lab and in the field under varying compaction levels. The following section provides the summary of findings from each of these studies.

6.1.1 Survey of Contractors and Midwestern Highway Agencies

In order to gather recent information about requirements implemented by different state highway agencies for compaction of Superpave mixtures, a survey questionnaire was sent to twelve midwestern state highway agencies and to contractors in Wisconsin. Contractors represented varied in their responses as to what the minimum pavement thickness should be. Responses ranged from as low as 1.75 times the nominal maximum aggregate size, to as high as 4. The Midwestern DOT's indicated a much tighter band of responses; with most stating that a range of 3 to 4 times the nominal maximum aggregate size was best. Searches of the WisDOT databases revealed no major problems in achieving density in the field.

6.1.2 Laboratory Study

During the field study, several key findings were noted. A summary of these is provided below.

- The results indicate, that during the laboratory phase, sample size, which defines sample thickness, was significant in defining density after a selected number of gyrations. For all mixtures tested in this project, samples that were less than 3,000 grams consistently demonstrated higher air voids than the samples larger than 3,000 grams. It was also found that reducing sample sizes below 3,000 grams resulted in more compaction energy required to achieve 92 % G_{mm} along with higher friction measured for these samples. The ratio of air voids of a 1500 gram sample to the air voids of 3000 gram sample ranged between a low of 1.26 and a high of 1.95 at N_{des} gyrations. Given the target of 4% air voids at N_{des}, these ratios represented a change in voids content between 1% and approximately 3.5%, which are considered significant differences. Samples larger than 3000 grams did not show air voids significantly higher than the 3000 gram sample sizes, and in some cases increasing the sample size to 6000 grams resulted in slightly reduced air voids and less compaction energy to reach 92 % G_{mm}.
- Factors other than the ratio of thickness to nominal maximum aggregate size were also varied to study possible interactive effects. A statistical analysis was conducted to study the importance of the other factors including aggregate source (type), gradation, and nominal maximum size of aggregates. The results of the ANOVA analysis indicate that the other factors were not as significant as the ratio of sample size to maximum aggregate size. It was observed, that including the source of aggregates is useful in explaining the change in air voids content as the sample thickness is changed. The analysis indicted that although source and gradation were not found to be highly significant, the coefficient of determination could be improved significantly by including the source, gradation, maximum size, and two-way interactive effects. These results indicate that although the

sample size is the dominating factor, the change in air voids due to sample size is mixture source specific. Based on this observation, to recommend one ratio of lift thickness to maximum aggregate for all sources of aggregates could be misleading. A contractor should have a tool and a test method to estimate the effect of lift thickness on compaction for the specific project aggregates. This however is based on the assumption that the data collected in the lab using the gyratory compactor realistically simulated field conditions.

- The gradation of recovered aggregates from all the samples were measured after compaction and compared. The results indicate that the crushing of aggregates in the SGC proved to be minor, and is not dependent on the size of sample being compacted.

6.1.3 Field Study

A total of four field projects were included in this study. The following summarizes the important findings.

- There is no clear indication that the change in lift thickness had an important effect on the final density achieved for a given number of roller passes. This was proven statistically, even with low R^2-valules of the models.
- There are many other factors that can have an effect on the final density achieved in the field, including the climactic conditions of the day, inconsistencies in the production of mixes, and the base on which the pavement is being constructed. Controlling these factors and holding them constant between projects or within a project was very difficult.
- The field results collected for the same ratios of lift thickness to maximum aggregate size and for the sample thickness did not align with the laboratory results. Testing in the laboratory demonstrated that the air voids of samples compacted at ratios of thickness to

nominal maximum aggregate size of less than 3.0 are significantly higher than samples compacted at higher ratios, which was not confirmed in the field. In fact the field data indicated that higher lift thickness required more roller passes than thin lifts to achieve density.

- To explain differences between laboratory and field, a limited size experiment was conducted in which the samples were compacted on an aggregate layer in the compactor mold simulating a softer base layer. It appears that softening the base of the compaction mold could result in significant reduction in air voids. Sources were limited to fully explore this behavior and more work is required to explain the difference between laboratory and field. Such work is necessary to develop a tool that would allow evaluating effect of lift thickness on compaction resistance in the laboratory.

6.2 CONCLUSIONS

Based on the laboratory study, using the Superpave Gyratory Compactor, it can be concluded that the sample size (sample thickness) has an important effect on achieving required density. A ratio of sample thickness to maximum aggregate size in the range of 4-6 is required to ensure that sample thickness will not interfere with achieving density. The results also indicated that the minimum ratio required is somewhat affected by aggregate source and gradation.

The field study results, however, could not be used to confirm the findings from the laboratory study. There was no evidence that lift thicknesses below the ratio of 3.0 require more compaction to achieve density. This discrepancy between lab and field is difficult to explain. There are a number of factors that could be involved. More research is needed to explain the difference and to develop a procedure that would allow estimating the optimum lift thickness in the field required to achieve density.

6.3 RECOMMENDATIONS

Given the lack of correlation between field and laboratory data, recommendations to change the current recommendations and practice of the Wisconsin Department of Transportation and Wisconsin contractors would be difficult. Recommendations for future research include the following:

- Conduct more field studies using some of the more problematic mixes currently being used to check for the effect of thickness. In addition, control as many external variables as possible, including roller pattern and only testing when the mix quality control is on target and consistent.
- Test other types of the mixes that have not been looked at in this study in order to see if they exhibit the same behavior seen in this project.
- Continue to study the compaction process in the SGC to see if there is a way of modeling the compaction of mixes in the lab that can correlate directly to the field.

APPENDIX A

SURVEY QUESTIONNAIRE

Contractor Survey

University of
Wisconsin-Madison

Department of Civil and Environmental Engineering

3346 Engineering Building
1415 Johnson Drive
Madison, Wisconsin 53706
Telephone: (608) 263-1949
FAX: (608) 262-5199
bcpaye@students.wisc.edu

To:
From: Barry Paye – University of Wisconsin-Madison
RE: SUPERPAVE Layer Thickness
Date: February 14, 2001

In January of 2000, a research project began at UW-Madison to study the effects of SUPERPAVE layer thickness on compaction and field density. In the past, the guidelines were recommended for the use of SUPERPAVE mixtures, but no real studies have been performed to determine compaction guidelines or optimal lift thickness. This project, funded by the Wisconsin Department of Transportation and sponsored by its Flexible Pavement Technical Oversight Committee (TOC), is to determine what difficulties exist in compacting SUPERPAVE mixtures and to recommend a minimum lift thickness for use.

During 2000, a laboratory study was conducted to get an idea of how lift thickness may affect density of SUPERPAVE mixtures. A field study was also conducted to see how lift thickness could affect the density on a paving job. The results of these initial steps are promising, and further study is planned for the spring and summer of 2001.

The purpose of this memo and attached survey is to find out how the paving industry feels about the compaction of SUPERPAVE mixtures and to get an understanding of any problems that may be occurring in application, especially as they relate to lift thickness. This information will help guide UW-Madison and the DOT in recommending a minimum lift thickness for SUPERPAVE mixtures. We appreciate your feedback. Please feel free to attach more sheets if more room is needed to respond to a question**. Please respond by March 15, 2001**.

If you have any questions, please don't hesitate to contact me at the following:

Phone: (608) 263-1949
Fax: (608) 265-9860
Email: bcpaye@students.wisc.edu

Thank you for your time and input.

Name:______________________Company/Agency:____________________________
Contact information:____

1. Has your company/agency had any problems with compacting SUPERPAVE mixes of any type?
   (If yes, describe the nature of the problem in detail, if no, simply say "NO" and fax this form back to the number listed below.)

   Yes No

2. Have certain SUPERPAVE mixtures (coarse, crushed limestone, etc.) provided more resistance to compaction or more difficulty in achieving the required density than other mixes? If so, please explain.

3. Have certain lift thicknesses for SUPERPAVE mixtures proved to be more difficult to compact than others? If so, please describe.

4. Based off your experience, what is the minimum lift thickness you could recommend?

5. Would you be willing to participate in field studies looking at SUPERPAVE layer thickness this spring or summer? If so, list a person who would be good to contact in order to organize such a project or to give further information.

Thank you for your consideration and let me know if you have any questions.
Fax to: Barry Paye (608) 265-9860

State Agency Survey

University of
Wisconsin-Madison

Department of Civil and Environmental Engineering

3338 Engineering Building
1415 Johnson Drive
Madison, Wisconsin 53706
Telephone: (608) 265-4481
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e-Mail bahia@engr.wisc.edu

To:
Fax:
From: Barry Paye, UW-Madison Asphalt Group
Date: June 21, 2000
Subject: SUPERPAVE Layer Thickness Survey

Currently, UW-Madison is working on a project for the Wisconsin DOT to study the effect of SUPERPAVE layer thickness on the amount of compaction (Air Voids) and condition of the aggregates in the pavement. Please forward this survey to someone in who deals with this topic. Your help is greatly appreciated.

1. Name of Person Completing Survey:________________________________.

2. Do you have layer thickness limitations for SUPERPAVE mixtures? If yes, please list them.
____
____

3. Does your layer thickness depend on the Nominal Maximum aggregate size for SUPERPAVE mixtures? If yes, explain how.

4. Do contractors in your state have problems in achieving the desired amount of compaction in SUPERPAVE mixes? If yes, explain the nature of the problem.

5. Does your state allow higher air voids in SUPERPAVE mixtures?

6. Do you think there is a permeability problem with SUPERPAVE mixtures? Is your agency addressing these issues?

Thank you for your help. If you have any questions, please contact Barry Paye at bcpaye@students.wisc.edu, or call (608) 263-1949, or fax (608) 262 – 5199.

APPENDIX B

LABORATORY AIR VOID ANALYSIS: FIGURES AND TABLES

Source L Coarse: 19mm Data Sheet

Design # : 503299 **Tested By:** *Brian Poehnelt Barry Paye*

Mix Type : 19.0 mm

Agg Type : Lime Stone

Material : Source L

% Binder : 4.60%

Code:	**19**	**LC**	**15**	**A**
	Nominal Max.Size	**Quarry/Pit Source L**	**Size (x 100)**	**Sample indicator**

Comments:

0.5% dust was added to mix.

Sample	**19LR1**	**19LR2**
Wt.of mix and pot:	5010.1	5025.4
Wt.of pot:	2943.2	2943.2
Wt. of mix	2066.9	2082.2
Wt.of mix+pot+$H_2$0:	8744.1	8750.2
Calibration Volume:	4534.2	4534.2
	3734	3724.8
	800.2	809.4
Water absorbed	1.5	1.6
	801.7	811
Gmm	2.578	2.567
Average Gmm:	2.573	

Compacted to N_{des}: 109 gyrations

Sample	Ave. Thickness (mm)	Thickness/ Max. Size	Dry Wt.	Wt. In H2O	SSD. Wt.	Gmb	Air Voids	Average
19L15A	40.61	2.14	1564	916.8	1585.7	2.338	9.1	
19L15B	40.45	2.13	1573.3	921.5	1593.7	2.341	9.0	9.1
19L20A	51.10	2.69	2056	1207.1	2072.5	2.376	7.7	
19L20B	53.81	2.83	2083.5	1216.6	2095	2.372	7.8	7.7
19L25A	64.45	3.39	2624.7	1540.3	2634.8	2.398	6.8	
19L25B	64.30	3.38	2628.6	1544.9	2639.1	2.402	6.6	6.7
19L30A	75.01	3.95	3067.4	1808	3084.2	2.404	6.6	
19L30B	74.50	3.92	3090.2	1824.9	3099.7	2.424	5.8	6.2
19L47A	116.67	6.14	4933.5	2929	4941.1	2.452	4.7	
19L47B	115.76	6.09	4930.1	2938.2	4938	2.465	4.2	4.4
19L60A	148.68	7.83	6286.9	3729.9	6300.3	2.446	4.9	
19L60B	148.78	7.83	6263.1	3706.4	6278.5	2.435	5.4	5.1

Compacted at 200 gyrations

Sample	Ave. Thickness (mm)	Thickness/ Max. Size	Dry Wt.	Wt. In H2O	SSD. Wt.	Gmb	Air Voids
19L15D	40.57	2.14	1592.9	937.7	1614	2.355	8.5
19L20C1	51.16	2.69	2083.6	1227.7	2094.5	2.404	6.6
19L25C1	63.27	3.33	2606.3	1541.7	2618	2.422	5.9
19L30C1	75.28	3.96	3138.6	1860	3149.5	2.434	5.4
19L47C1	113.89	5.99	4912.7	2955	4920.4	2.500	2.8
19L60D	146.85	7.73	6291.3	3755.2	6297.9	2.474	3.8

Source L Coarse: 12.5mm Data Sheet

Design # :	503399	**Tested By:**	*Brian Poehnelt & Barry Paye*				
Mix Type :	12.5 mm						
Agg Type :	Lime Stone	**Sample Code:**	**12.5**	L	**15**	**A**	
Material :	Source L		**Nominal**	**Quarry/Pit**	**Size**	**Sample**	
% Binder :	5.30%		**Max.Size**	**Source L**	**(x 100)**	**indicator**	

Comments:

0.5% dust was added to mix.

Sample	**12.5LR1**	**12.5LR2**
Wt.of mix and pot:	4981.8	4995.7
Wt.of pot:	2943.2	2943.2
Wt. of mix	2038.6	2052.5
Wt.of mix+pot+$H_2$0:	8719.6	8727.7
Calibration Volume:	4534.2	4534.2
	3737.8	3732
	796.4	802.2
Water absorbed	0.3	0.6
	796.7	802.8
Gmm	2.559	2.557
Average Gmm:	2.558	

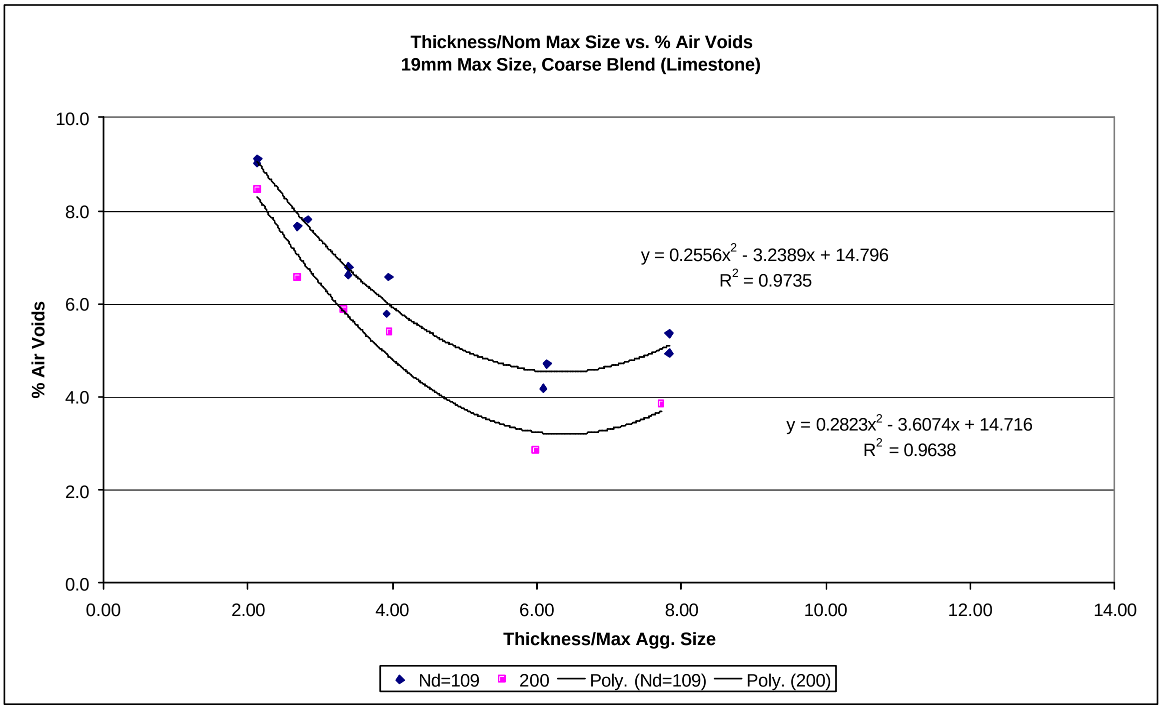
Compacted to N_{des}: 109 gyrations

Sample	Ave. Thickness (mm)	Thickness/ Max Size	Dry Wt.	Wt. In H2O	SSD. Wt.	Gmb	Air Voids	Average
12.5L15A	40.33	3.23	1566	913.8	1580.2	2.350	8.1	
12.5L15B	41.03	3.28	1559.2	908.3	1578.9	2.325	9.1	8.6
12.5L20E	52.35	4.19	2098.9	1223.4	2108.4	2.372	7.3	
12.5L20B	51.71	4.14	2070.9	1211	2083.8	2.373	7.2	7.3
12.5L25D	64.34	5.15	2601.5	1526.1	2613	2.394	6.4	
12.5L25E	64.46	5.16	2623.9	1541.1	2633.7	2.402	6.1	6.3
12.5L30E	75.68	6.05	3145.4	1863.1	3152.3	2.440	4.6	
12.5L30D	75.60	6.05	3152.4	1868.4	3158.4	2.444	4.5	4.5
12.5L47D	116.40	9.31	4911.8	2929.7	4917.5	2.471	3.4	
12.5L47E	116.49	9.32	4922.9	2943.3	4928.2	2.480	3.0	3.2
12.5L60A	149.61	11.97	6314	3745.8	6324	2.449	4.3	
12.5L60B	147.91	11.83	6304	3751.8	6310.7	2.464	3.7	4.0

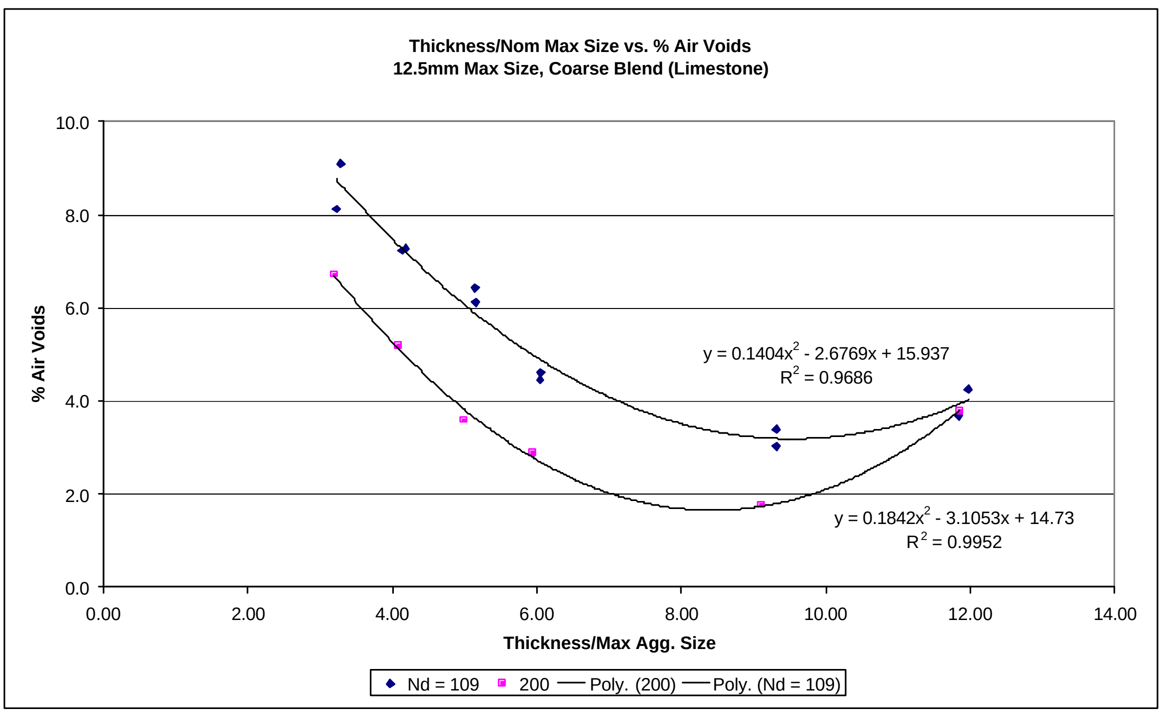
Compacted at 200 gyrations

Sample	Ave. Thickness (mm)		Dry Wt.	Wt. In H2O	SSD. Wt.	Gmb	Air Voids
12.5L15C	39.96	3.20	1592.4	935.3	1602.7	2.386	6.7
12.5L20C	51.09	4.09	2099.6	1239.8	2105.6	2.425	5.2
12.5L25C	62.38	4.99	2619.3	1561.2	2623.4	2.466	3.6
12.5L30C	74.32	5.95	3152.5	1886.7	3155.9	2.484	2.9
12.5L47C	113.83	9.11	4936.8	2976	4940.7	2.513	1.8
12.5L60D	148.13	11.85	6306.4	3751.1	6313.6	2.461	3.8

Source L Coarse Plots



19mm Coarse Limestone, Source L Air Void Plot



12.5mm Coarse Limestone, Source L Air Void Plot

Source L Fine: 19mm Data Sheet

Design # :	BP Design	**Tested By:**	*Barry Paye*
Mix Type :	19.0 mm		
Agg Type :	Lime Stone		
Material :	Source L		
% Binder :	6.10%		

Code:	**19**	**L**	**F**	**15**	**A**
	Nominal	**Quarry/Pit**	**Gradation**	**Size**	**Sample**
	Max.Size	**Source L**	**Fine**	**(x 100)**	**indicator**

Comments:

Sample	**19LFR3**	**19LFR2**
Wt.of mix and pot:	5058.5	5048.4
Wt.of pot:	2943.2	2943.2
Wt. of mix	2115.3	2105.2
Wt.of mix+pot+$H_2$0:	8751.1	8745.4
Calibration Volume:	4534.2	4534.2
	3692.6	3697
	841.6	837.2
Water absorbed	0	0
	841.6	837.2
Gmm	2.513	2.515
Average Gmm:	2.514	

Compacted to N_{des}: 100 gyrations

Sample	Ave. Thickness (mm)	Thickness/ Max. Size	Dry Wt.	Wt. In H2O	SSD. Wt.	Gmb	Air Voids	Average
19LF15D	41.06	2.16	1596.4	913	1608.3	2.296	8.7	
19LF15E	40.37	2.12	1582.7	913.3	1596.8	2.316	7.9	8.3
19LF20D	52.02	2.74	2103.9	1220.2	2110.2	2.364	6.0	
19LF20E	52.22	2.75	2103.8	1218.8	2111.7	2.356	6.3	6.1
19LF30F	76.80	4.04	3177.4	1862.6	3184.3	2.404	4.4	
19LF30B	75.84	3.99	3144	1844	3148	2.411	4.1	4.2
19LF47F	117.20	6.17	4950.1	2924.8	4954.9	2.438	3.0	
19LF47G	119.02	6.26	4981.5	2925	4987	2.416	3.9	3.5
19LF60A	151.11	7.95	6336.7	3713.6	6342.7	2.410	4.1	
19LF60B	150.52	7.92	6306.1	3701.5	6310.2	2.417	3.8	4.0

Compacted Nmax: 160 gyrations

Sample	Ave. Thickness (mm)		Dry Wt.	Wt. In H2O	SSD. Wt.	Gmb	Air Voids
19LF15C	39.10	2.06	1563.6	894.2	1566.3	2.326	7.5
19LF20C	52.34	2.75	2101.1	1221.6	2108.4	2.369	5.8
19LF30C	75.31	3.96	3153.6	1858.9	3156.9	2.430	3.4
19LF47E	115.60	6.08	4960.6	2959.4	4963.8	2.475	1.6
19LF60C	151.31	7.96	6338.2	3721.8	6345.1	2.416	3.9

Source L Fine: 12.5mm Data Sheet

Design # :	BP Design	**Tested By:**	*Barry Paye*
Mix Type :	12.5 mm		
Agg Type :	Lime Stone		
Material :	Source L		
% Binder :	6.10%		

Code:	**12.5**	**L**	**F**	**15**	**A**
	Nominal Max.Size	**Quarry/Pit Source L**	**Gradation Fine**	**Size (x 100)**	**Sample indicator**

Sample	**12.5LFR1**	**12.5LFR2**
Wt.of mix and pot:	4527.4	4527
Wt.of pot:	2943.2	2943.2
Wt. of mix	1584.2	1583.8
Wt.of mix+pot+$H_2$0:	8422.5	8423.5
Calibration Volume:	4534.2	4534.2
	3895.1	3896.5
	639.1	637.7
Water absorbed	0	0
	639.1	637.7
Gmm	2.479	2.484
Average Gmm:	2.481	

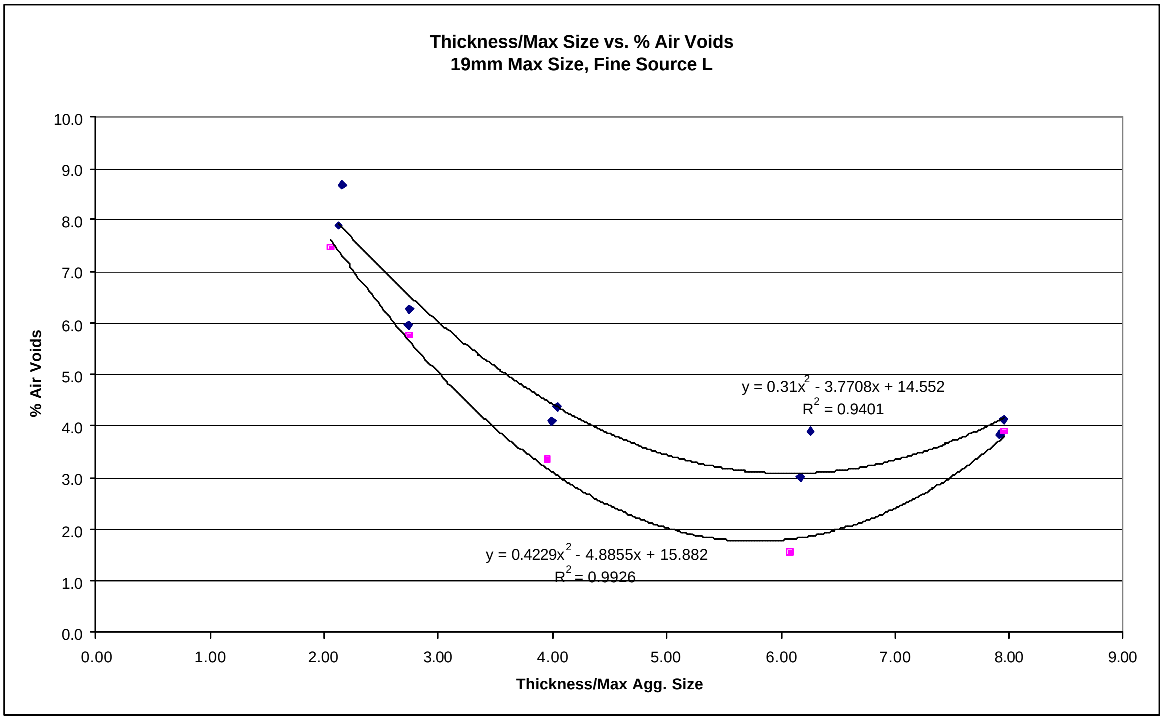
Compacted to N_{des}: 100 gyrations

Sample	Ave. Thickness (mm)	Thickness/ Max Size	Dry Wt.	Wt. In H2O	SSD. Wt.	Gmb	Air Voids	Average
12.5LF15A	39.07	3.13	1556.8	897.4	1570.7	2.312	6.8	
12.5LF15B	39.79	3.18	1580	900.3	1583.6	2.312	6.8	6.8
12.5LF20A	51.91	4.15	2092	1199.3	2095.7	2.334	5.9	
12.5LF20D	52.17	4.17	2100.9	1204.5	2102.9	2.338	5.8	5.8
12.5LF30D	77.44	6.19	3157.3	1818	3160.5	2.352	5.2	
12.5LF30B	76.84	6.15	3140.5	1810.8	3144.8	2.354	5.1	5.2
12.5LF47D	120.12	9.61	4952.9	2882	4957.7	2.386	3.8	
12.5LF47E	119.57	9.57	4987.7	2903.2	4992.6	2.387	3.8	3.8
12.5LF60A	153.05	12.24	6340.8	3667.5	6347	2.366	4.6	
12.5LF60B	153.79	12.30	6296.1	3624.3	6305.6	2.348	5.4	5.0

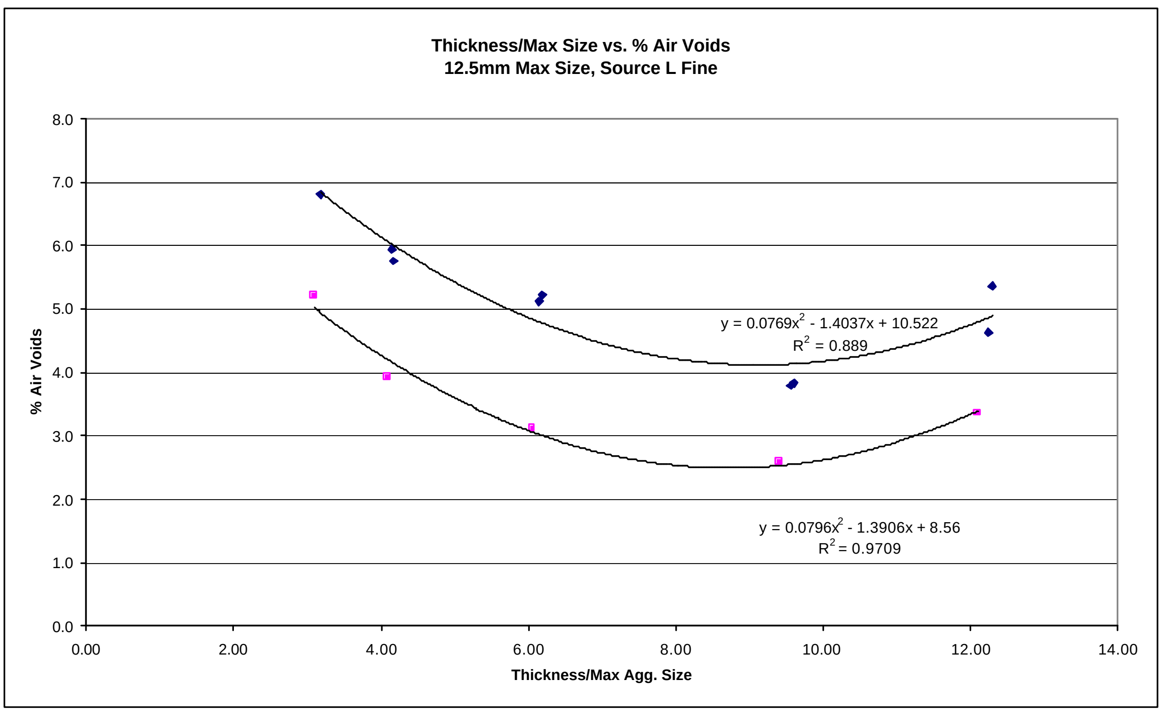
Compacted at 160 gyrations

Sample	Ave. Thickness (mm)		Dry Wt.	Wt. In H2O	SSD. Wt.	Gmb	Air Voids
12.5LF15C	38.63	3.09	1564.6	903.7	1568.9	2.352	5.2
12.5LF20C	51.08	4.09	2099.2	1220.3	2101	2.384	3.9
12.5LF30C	75.62	6.05	3154.1	1843.4	3155.6	2.404	3.1
12.5LF47E	117.59	9.41	4958.2	2909.1	4960.5	2.417	2.6
12.5LF60C	151.32	12.11	6338.9	3697.9	6341.6	2.398	3.4

Source L Fine Plots



19mm Fine Limestone, Source L Air Void Plot



12.5mm Coarse Limestone, Source L Air Void Plot

Source K, 19mm Data Sheet

Design # : 505800
Mix Type : 19.0 mm
Agg Type : Gravel
Material : Source K
% Binder : 4.30%

Tested By: *Barry Paye*

Code:	**19**	**K**	**15**	**A**
	Nominal Max.Size	**Pit Source K**	**Size (x 100)**	**Sample indicator**

Comment

Field Samples Collected on 8/23/00

Sample	**#1**	**#2**
Wt. of mix	2221	2087
Wt.of mix+pot+$H_2$0:	8830.9	8745.1
Gmm	2.560	2.547
Average Gmm:	2.554	

Compacted to N_{des}: 75 gyrations

Sample	Ave. Thickness (mm)	Thickness/ NM	Dry Wt.	Wt. In H2O	SSD. Wt.	Gmb	Air Voids	Average
19K15C	37.73	1.99	1513.3	873.5	1519.1	2.344	8.2	
19K15B	38.67	2.04	1544.2	890.7	1553.3	2.331	8.7	8.5
19K20A	50.66	2.67	2076.6	1212.4	2083.7	2.383	6.7	
19K20B	50.08	2.64	2068.3	1209.9	2073.9	2.394	6.3	6.5
19K25A	60.81	3.20	2521.3	1470.2	2526.1	2.388	6.5	
19K25B	62.20	3.27	2586.2	1512.6	2590.8	2.399	6.1	6.3
19K30A	72.96	3.84	3022.1	1762.5	3028.6	2.387	6.5	
19K30B	71.64	3.77	2995.8	1754.1	2999.1	2.406	5.8	6.1
19K47A	113.15	5.96	4714.8	2760.8	4726.6	2.398	6.1	
19K47B	112.19	5.90	4720.3	2770.1	4728.9	2.410	5.6	5.9
19K60A	143.30	7.54	6011.4	3514.4	6022.2	2.397	6.1	
19K60B	144.67	7.61	6052.4	3542	6066	2.398	6.1	6.1

Compacted at 115 gyrations

Sample	Ave. Thickness (mm)		Dry Wt.	Wt. In H2O	SSD. Wt.	Gmb	Air Voids
19K15D	40.57	2.14	1579.7	918.2	1583.9	2.373	7.1
19K20D	49.97	2.63	2019	1179.4	2020.8	2.400	6.0
19K30D	71.64	3.77	3146.9	1847.8	3151.7	2.413	5.5
19K47D	111.99	5.89	4717.9	2769.8	4723.6	2.415	5.4
19K60D	142.45	7.50	6076.4	3561.3	6085.3	2.407	5.7

Source K, 12.5mm Data Sheet

Design # : 505900 **Tested By:** *Barry Paye*

Mix Type : 12.5 mm

Agg Type : Gravel

Material : Source K

% Binder : 5.10%

Code:	12.5	K	15	A
	Nominal Max.Size	Quarry/Pit Source K	Size (x 100)	Sample indicator

Comments:

Field Samples Collected on 8/23/00

Sample	#1	#2
Wt.of mix and pot:	4473	4589.2
Wt.of pot:	2943.2	2943.2
Wt. of mix	1529.8	1646
Wt.of mix+pot+$H_2$0:	8401	8472.5
Gmm	2.524	2.529
Average Gmm:	2.527	

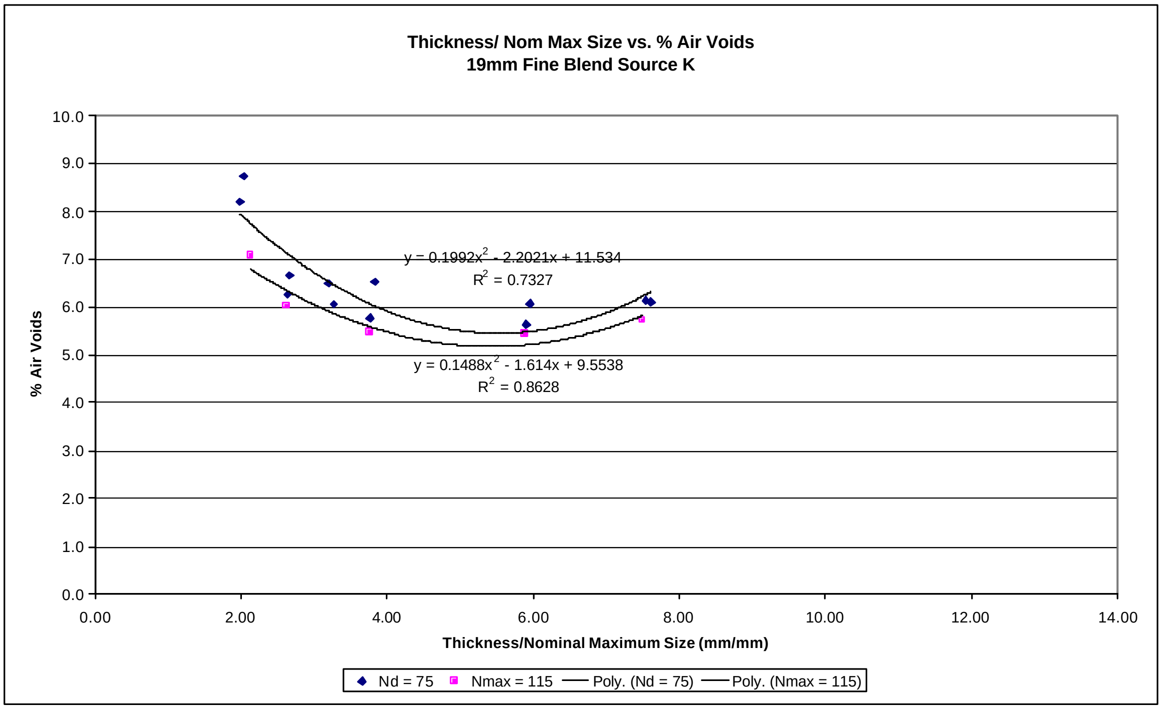
Compacted to N_{des}: 75 gyrations

Sample	Ave. Thickness (mm)	Thickness/ Nom. Max	Dry Wt.	Wt. In H2O	SSD. Wt.	Gmb	Air Voids	Average
12.5K15A	38.45	3.08	1593.3	919.9	1595.3	2.359	6.6	
12.5K15B	37.35	2.99	1525	881.6	1528.1	2.359	6.6	6.6
12.5K20A	50.10	4.01	2083.5	1206.5	2085.5	2.370	6.2	
12.5K20B	52.03	4.16	2188.1	1277.9	2189.8	2.399	5.0	5.6
12.5K30A	73.23	5.86	3108.7	1815.6	3110.7	2.400	5.0	
12.5K30B	72.77	5.82	3106.8	1822.2	3108.6	2.415	4.4	4.7
12.5K47A	109.51	8.76	4701.7	2759.4	4703.9	2.418	4.3	
12.5K47B	111.45	8.92	4797.1	2824.6	4799.3	2.429	3.8	4.1
12.5K60A	142.50	11.40	6086.5	3556.3	6091.2	2.401	5.0	
12.5K60B	144.35	11.55	6177.5	3611.3	6180.8	2.404	4.8	4.9

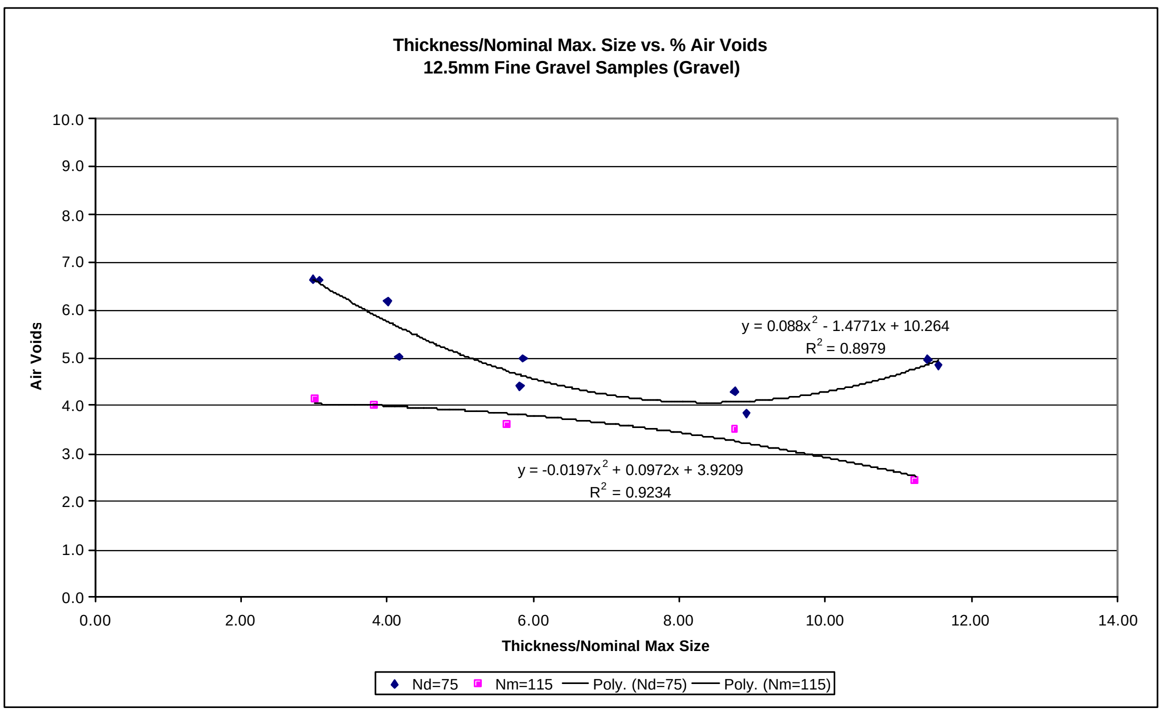
Compacted at115 gyrations

Sample	Ave. Thickness (mm)		Dry Wt.	Wt. In H2O	SSD. Wt.	Gmb	Air Voids
12.5K15C	37.70	3.02	1593.8	936.8	1594.8	2.422	4.1
12.5K20C	47.96	3.84	2053.7	1207.7	2054.4	2.426	4.0
12.5K30C	70.56	5.64	3043.1	1794.5	3044	2.435	3.6
12.5K47C	109.64	8.77	4756.3	2806.4	4757.4	2.438	3.5
12.5K60C	140.47	11.24	6094.9	3597	6069.4	2.465	2.4

Source K Plots



19mm Fine Gravel, Source K Air Void Plot



12.5mm Fine Gravel, Source K Air Voids Plot

Source M, 19mm Data Sheet

Design # : **Tested By:** *Barry Paye*

Mix Type :

Agg Type :

Material : Source M

% Binder :

Code:	**19**	**M**	**15**	**A**
	Nominal Max.Size	**Quarry/Pit Source M**	**Size (x 100)**	**Sample indicator**

Comments:

Sample	**19MR1**	**19MR2**
Wt.of mix and pot:	5059.8	5040
Wt.of pot:	2943.2	2943.2
Wt. of mix	2116.6	2096.8
Wt.of mix+pot+$H_2$0:	8729.3	8718.4
Calibration Volume:	4534.2	4534.2
	3669.5	3678.4
	864.7	855.8
Water absorbed	0	0
	864.7	855.8
Gmm	2.448	2.450
Average Gmm:	2.449	

Compacted to N_{des}: 100 gyrations

Sample	Ave. Thickness (mm)	Thickness/ Max. Size	Dry Wt.	Wt. In H2O	SSD. Wt.	Gmb	Air Voids	Average
19M15A	39.26	2.07	1471.2	839.2	1485.5	2.276	7.0	
19M15B	40.93	2.15	1546.1	885.8	1558.3	2.299	6.1	6.6
19M20A	53.94	2.84	2082.3	1202.5	2095.2	2.333	4.8	
19M20B	55.50	2.92	2164	1247.8	2176.8	2.329	4.9	4.8
19M30A	79.35	4.18	3168.7	1841.1	3183.4	2.361	3.6	
19M30B	74.23	3.91	2933.4	1702.1	2952.5	2.346	4.2	3.9
19M47A	118.31	6.23	4787.4	2775	4804.8	2.359	3.7	
19M47B	118.52	6.24	4808.8	2798.6	4824.1	2.374	3.1	3.4
19M60A	151.38	7.97	6141.6	3556.5	6156.6	2.362	3.5	
19M60B	150.19	7.90	6090.4	3539.6	6109.9	2.370	3.2	3.4

Compacted at 160 gyrations

Sample	Ave. Thickness (mm)		Dry Wt.	Wt. In H2O	SSD. Wt.	Gmb	Air Voids
19M15C1	42.25	2.22	1609.3	923.7	1621.1	2.308	5.8
19M20C1	51.67	2.72	2042.8	1184.4	2052.1	2.354	3.9
19M30C1	74.62	3.93	3032.5	1774.6	3041.6	2.393	2.3
19M47C1	114.63	6.03	4708.3	2752.8	4717.8	2.396	2.2
19M60C1	156.40	8.23	6426.3	3753	6440.1	2.392	2.3

Source M, 12.5mm Data Sheet

Design # : | **Tested By:** *Barry Paye*

Mix Type :

Agg Type :

Material : Source M

% Binder :

Code:	**12.5**	**M**	**15**	**A**
	Nominal	**Quarry/Pit**	**Size**	**Sample**
	Max.Size	**Source M**	**(x 100)**	**indicator**

Comments:

Sample	**12.5MR1**	**12.5MR2**
Wt.of mix and pot:	4531.4	4477.2
Wt.of pot:	2943.2	2943.2
Wt. of mix	1588.2	1534
Wt.of mix+pot+H_20:	8412.6	8379.1
Calibration Volume:	4534.2	4534.2
	3881.2	3901.9
	653	632.3
Water absorbed	0	0
	653	632.3
Gmm	2.432	2.426
Average Gmm:	2.429	

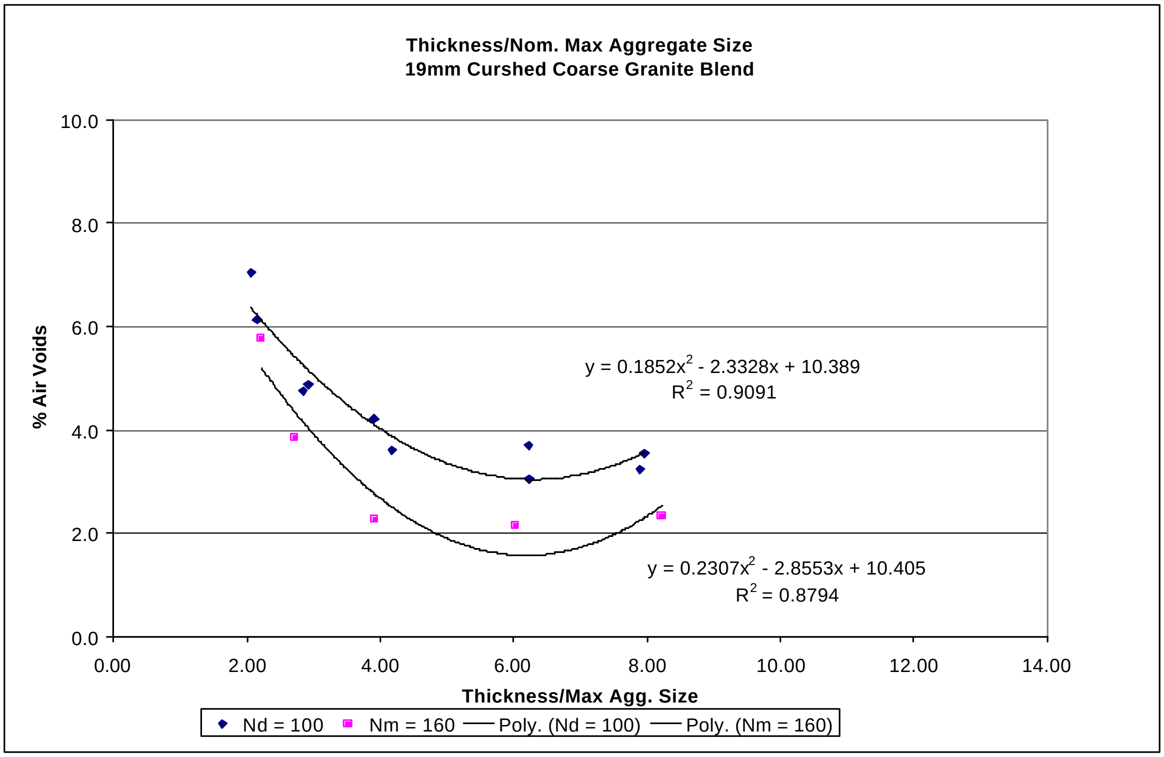
Compacted to N_{des}: 100 gyrations

Sample	Ave. Thickness (mm)	Thickness/ Max Size	Dry Wt.	Wt. In H2O	SSD. Wt.	Gmb	Air Voids	Average
12.5M15A	39.56	3.16	1548.1	881.5	1553.4	2.304	5.1	
12.5M15B	39.86	3.19	1569.5	887	1573	2.288	5.8	5.5
12.5M20A	50.78	4.06	2034	1164.9	2038.6	2.328	4.2	
12.5M20B	50.90	4.07	2035.9	1167.6	2039.6	2.335	3.9	4.0
12.5M30A	75.37	6.03	3059.5	1765.5	3064.7	2.355	3.1	
12.5M30B	77.51	6.20	3157.5	1821.5	3162.2	2.355	3.0	3.1
12.5M47A	117.51	9.40	4808.8	2768.4	4814.6	2.350	3.3	
12.5M47B	116.42	9.31	4743.7	2729.3	4752.3	2.345	3.5	3.4
12.5M60A	148.73	11.90	6085.7	3497	6091.7	2.345	3.4	
12.5M60B	148.93	11.91	6080.8	3494.5	6087.2	2.345	3.4	3.4

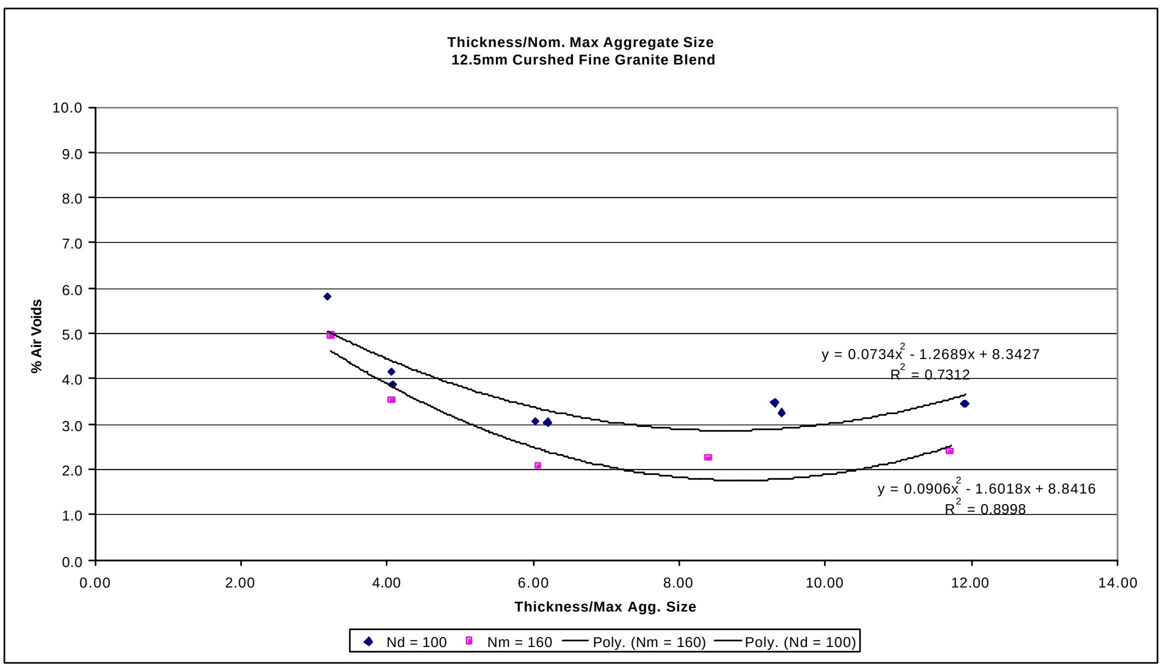
Compacted at 160 gyrations

Sample	Ave. Thickness (mm)		Dry Wt.	Wt. In H2O	SSD. Wt.	Gmb	Air Voids
12.5M15C	40.45	3.24	1594.3	908.6	1599.1	2.309	4.9
12.5M20C	50.97	4.08	2052.9	1179.7	2055.6	2.344	3.5
12.5M30C	75.89	6.07	3129.6	1817.7	3133.4	2.379	2.1
12.5M47C	105.11	8.41	4344.3	2520.1	4349.6	2.375	2.2
12.5M60C	146.5156667	11.72	6056.1	3506.9	6060.900	2.371	2.4

Source M Plots



19mm Coarse Granite, Source M Air Void Plot



12.5mm Fine Granite, Source M Air Void Plot

Source N, 19mm Data Sheet

Design # : **Tested By:** *Barry Paye*

Mix Type :

Agg Type :

Material : Source N

% Binder :

Code:	19	N	15	A
	Nominal Max.Size	Quarry/Pit Source N	Size (x 100)	Sample indicator

Comments:

Sample	19NR1	19NR2
Wt.of mix and pot:	4993.8	5075
Wt.of pot:	2943.2	2943.2
Wt. of mix	2050.6	2131.8
Wt.of mix+pot+$H_2$0:	8742	8795.9
Calibration Volume:	4534.2	4534.2
	3748.2	3720.9
	786	813.3
Water absorbed	0	0
	786	813.3
Gmm	2.609	2.621
Average Gmm:	2.615	

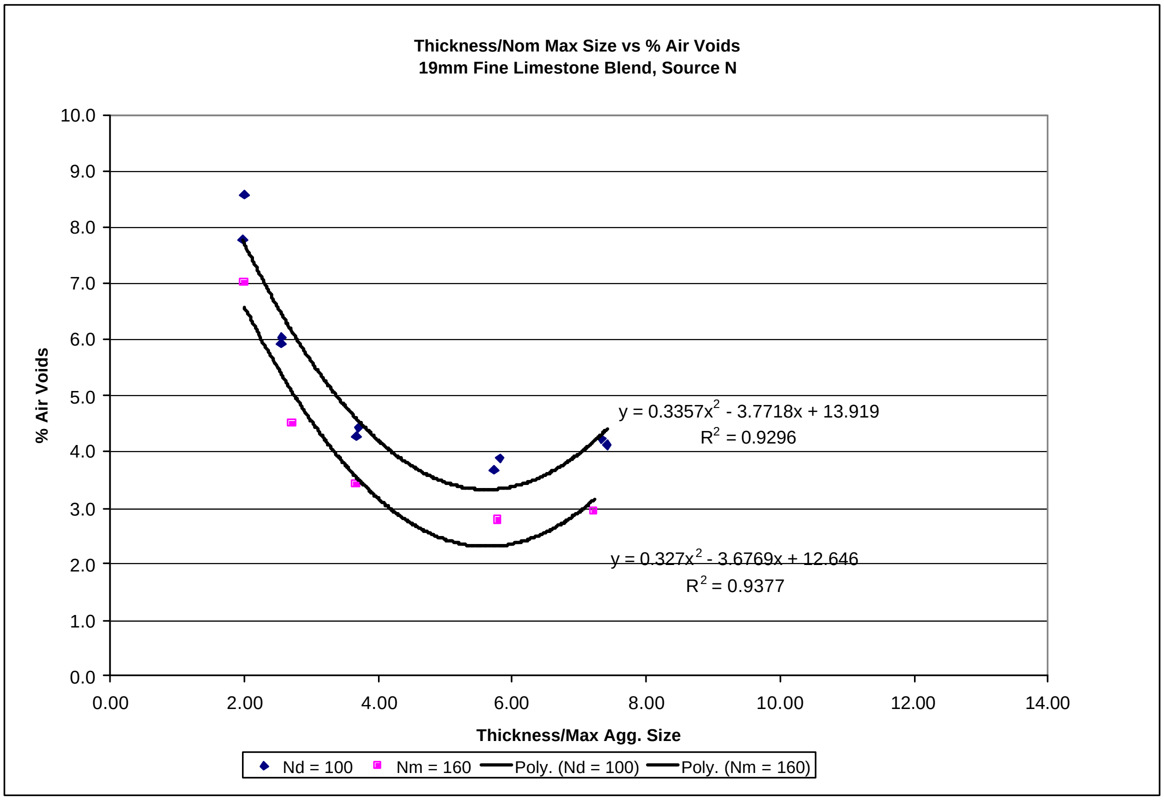
Compacted to N_{des}: 100 gyrations

Sample	Ave. Thickness (mm)	Thickness/ Max. Size	Dry Wt.	Wt. In H2O	SSD. Wt.	Gmb	Air Voids	Average
19N15A	37.69	1.98	1552.6	918.2	1562	2.412	7.8	
19F15B	38.20	2.01	1571.3	925.3	1582.6	2.391	8.6	8.2
19N20A	48.57	2.56	2060.1	1229	2066.4	2.460	5.9	
19N20B	48.64	2.56	2053.8	1225.7	2061.6	2.457	6.0	6.0
19N30A	70.52	3.71	3054.2	1837.9	3059.8	2.500	4.4	
19N30B	69.86	3.68	3033.2	1825.1	3036.7	2.503	4.3	4.3
19N47E	110.68	5.83	4826	2913	4833	2.514	3.9	
19N47B	108.96	5.73	4780.1	2885.4	4783	2.519	3.7	3.8
19N60A	139.32	7.33	6065.7	3649.3	6071.2	2.505	4.2	
19N60E	140.89	7.42	6138.2	3702.1	6150.1	2.507	4.1	4.2

Compacted at 160 gyrations

Sample	Ave. Thickness (mm)		Dry Wt.	Wt. In H2O	SSD. Wt.	Gmb	Air Voids
19N15D	38.12	2.01	1574.7	935.5	1583.1	2.432	7.0
19N20D	51.80	2.73	2217.3	1332.5	2220.4	2.497	4.5
19N30D	69.86	3.68	3028.7	1837.6	3036.8	2.526	3.4
19N47D	109.91	5.78	4858.7	2954.3	4865.4	2.542	2.8
19N60D	137.37	7.23	6072.9	3689.4	6081.9	2.538	2.9

Source N Plots



19mm Fine Limestone, Source N Air Void Plot

Source P, 19mm Data Sheet

Design # : | **Tested By:** *Barry Paye*

Mix Type :

Agg Type :

Material : Source P

% Binder :

Code:	**19**	**P**	**15**	**A**
	Nominal Max.Size	**Quarry/Pit Source P**	**Size (x 100)**	**Sample indicator**

Comments:

Sample	**19PR1**	**19PR2**
Wt.of mix and pot:	5026	5012.9
Wt.of pot:	2943.2	2943.2
Wt. of mix	2082.8	2069.7
Wt.of mix+pot+H_20:	8735.8	8726.6
Calibration Volume:	4534.2	4534.2
	3709.8	3713.7
	824.4	820.5
Water absorbed	0	0
	824.4	820.5
Gmm	2.526	2.522
Average Gmm:	2.524	

Compacted to N_{des}: 75 gyrations

Sample	Ave. Thickness (mm)	Thickness/ Max. Size	Dry Wt.	Wt. In H2O	SSD. Wt.	Gmb	Air Voids	Average
19P15A	39.81	2.10	1561.1	891.4	1570	2.300	8.9	
19P15B	40.28	2.12	1578.8	899.2	1591	2.282	9.6	9.2
19P20A	54.60	2.87	2189.5	1262.2	2199.9	2.335	7.5	
19P20B	50.54	2.66	2040.5	1178.1	2047.3	2.348	7.0	7.3
19P30A	74.45	3.92	3059.6	1781.1	3066.9	2.380	5.7	
19P30B	74.83	3.94	3083.2	1794.2	3088.7	2.382	5.7	5.7
19P47A	114.38	6.02	4751.7	2773.4	4760.1	2.392	5.3	
19P47B	114.82	6.04	4777.9	2780.7	4784.4	2.385	5.5	5.4
19P60A	145.28	7.65	6048.8	3525.7	6059.9	2.387	5.5	
19P60B	145.73	7.67	6048.6	3524.8	6063.8	2.382	5.6	5.5

Compacted at 115 gyrations

Sample	Ave. Thickness (mm)		Dry Wt.	Wt. In H2O	SSD. Wt.	Gmb	Air Voids
19P15C	40.23	2.12	1600.6	920.6	1607.1	2.332	7.6
19P20C	49.96	2.63	2044.1	1185	2048.2	2.368	6.2
19P30C	73.24	3.85	3067.2	1800.8	3070.8	2.415	4.3
19P47C	113.28	5.96	4750.7	2781.5	4755.2	2.407	4.7
19P60C	145.91	7.68	6122	3583.9	6128.3	2.406	4.7

Source P, 12.5mm Data Sheet

Design # : **Tested By:** *Barry Paye*

Mix Type :

Agg Type :

Material : Source P

% Binder :

Code:	**12.5**	**P**	**15**	**A**
	Nominal	**Quarry/Pit**	**Size**	**Sample**
	Max.Size	**Source P**	**(x 100)**	**indicator**

Comments:

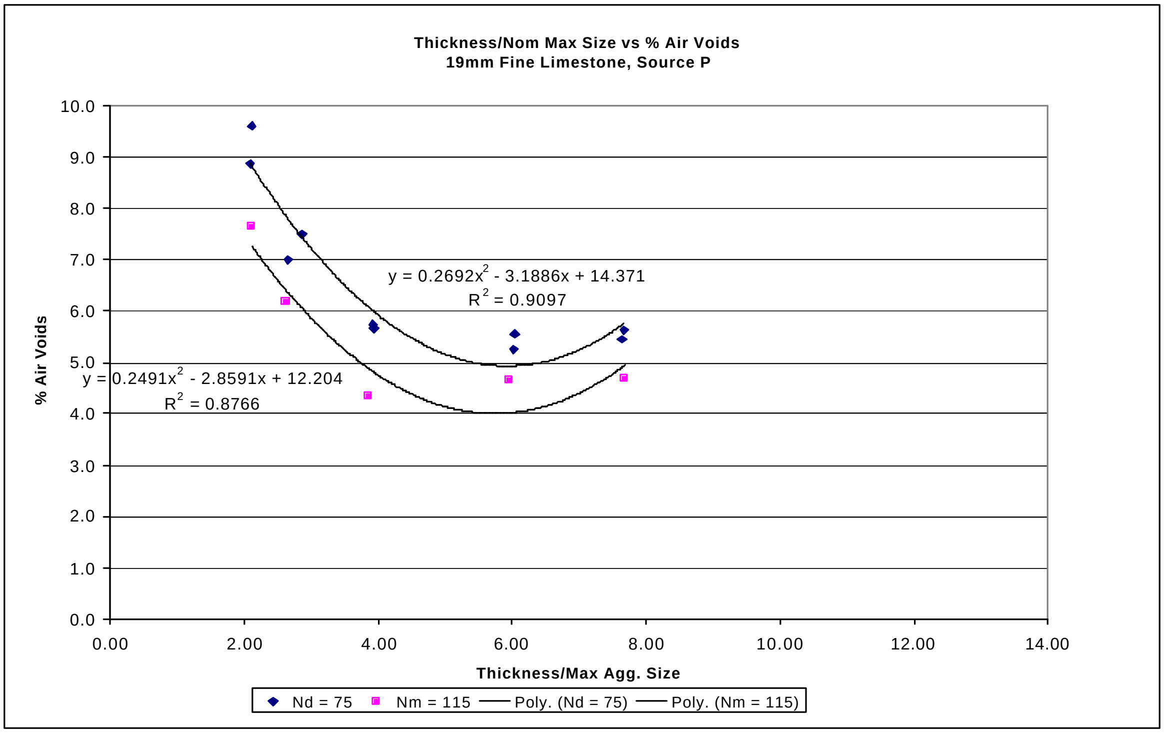
Sample	**12.5PR1**	**12.5PR2**
Wt.of mix and pot:	4992.4	5096.3
Wt.of pot:	2943.2	2943.2
Wt. of mix	2049.2	2153.1
Wt.of mix+pot+$H_2$0:	8706.2	8769.8
Calibration Volume:	4534.2	4534.2
	3713.8	3673.5
	820.4	860.7
Water absorbed	0	0
	820.4	860.7
Gmm	2.498	2.502
Average Gmm:	2.500	

Compacted to N_{des}: 75 gyrations

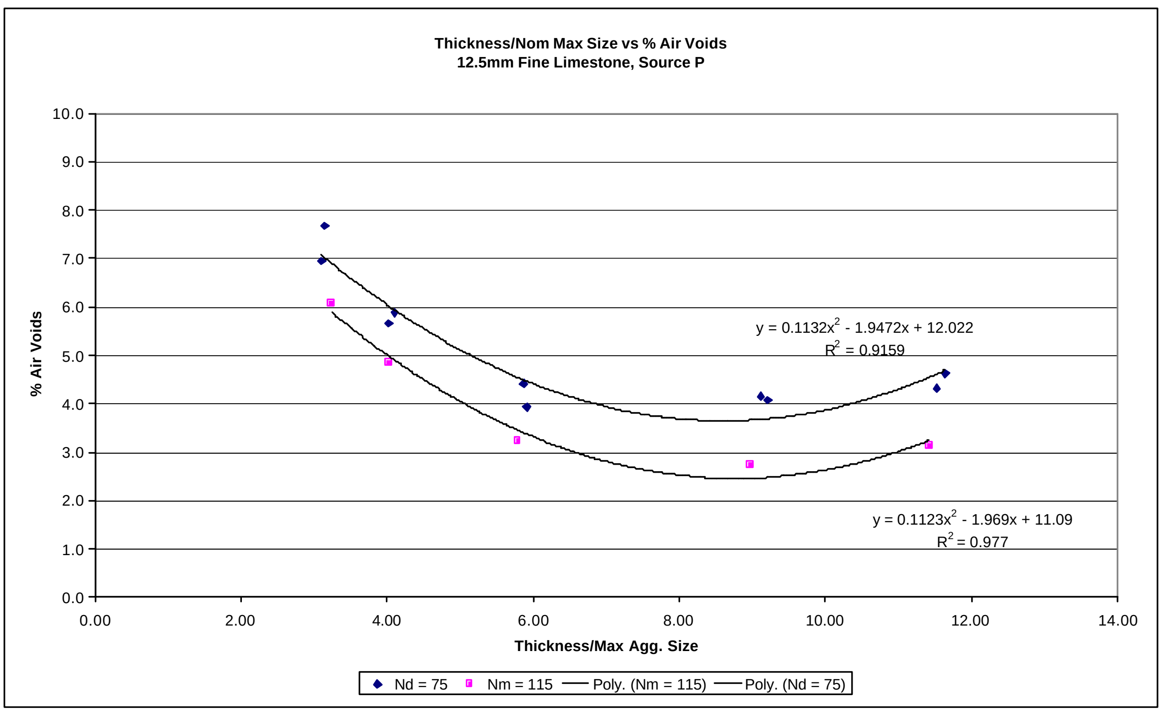
Sample	**Ave. Thickness (mm)**	**Thickness/ Max Size**	**Dry Wt.**	**Wt. In H2O**	**SSD. Wt.**	**Gmb**	**Air Voids**	**Average**
12.5P15A	38.83	3.11	1547.7	885.8	1551.2	2.326	6.9	
12.5P15D	39.34	3.15	1557.4	889.2	1564	2.308	7.7	7.3
12.5P20A	51.30	4.10	2074.6	1196.1	2077.9	2.353	5.9	
12.5P20B	50.24	4.02	2036.5	1176.1	2039.7	2.358	5.7	5.8
12.5P30A	73.97	5.92	3077.8	1798	3079.8	2.401	3.9	
12.5P30B	73.44	5.88	3033.5	1766.6	3036.2	2.389	4.4	4.2
12.5P47A	113.99	9.12	4760.5	2776.8	4763.6	2.396	4.1	
12.5P47B	115.21	9.22	4818.8	2813.8	4823.3	2.398	4.1	4.1
12.5P60A	145.56	11.64	6049.2	3518	6055.6	2.384	4.6	
12.5P60B	144.05	11.52	6013.5	3504.3	6018.6	2.392	4.3	4.5

Compacted at 115 gyrations

Sample	**Ave. Thickness (mm)**		**Dry Wt.**	**Wt. In H2O**	**SSD. Wt.**	**Gmb**	**Air Voids**
12.5P15C	40.58	3.25	1636.1	944.1	1640.9	2.348	6.1
12.5P20C	50.28	4.02	2048.3	1191.6	2052.8	2.378	4.9
12.5P30C	72.42	5.79	3025.5	1777.9	3028.8	2.419	3.2
12.5P47C	112.20	8.98	4733.9	2792.1	4739.1	2.431	2.7
12.5P60C	142.76	11.42	6022.5	3542.3	6029.6	2.421	3.1



19mm Fine Limestone, Source P Air Voids Plot

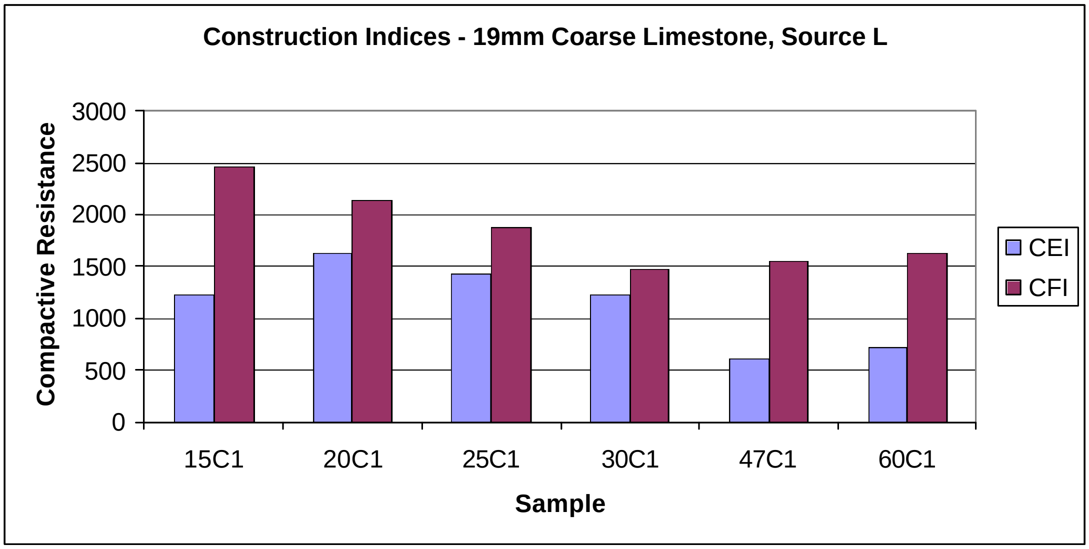


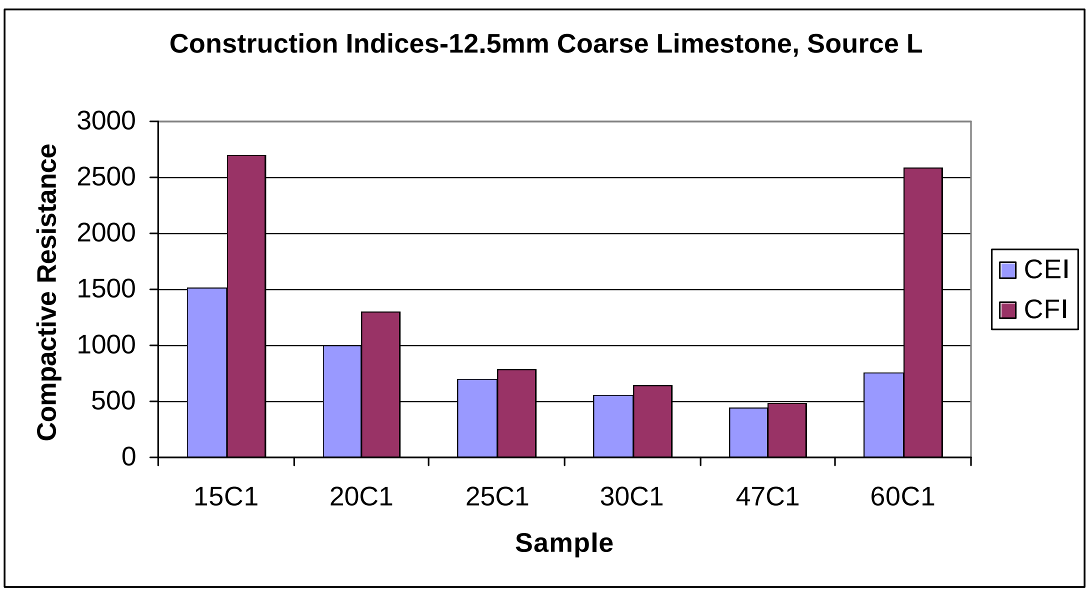
12.5mm Fine Limestone, Source P Air Voids Plot

APPENDIX C

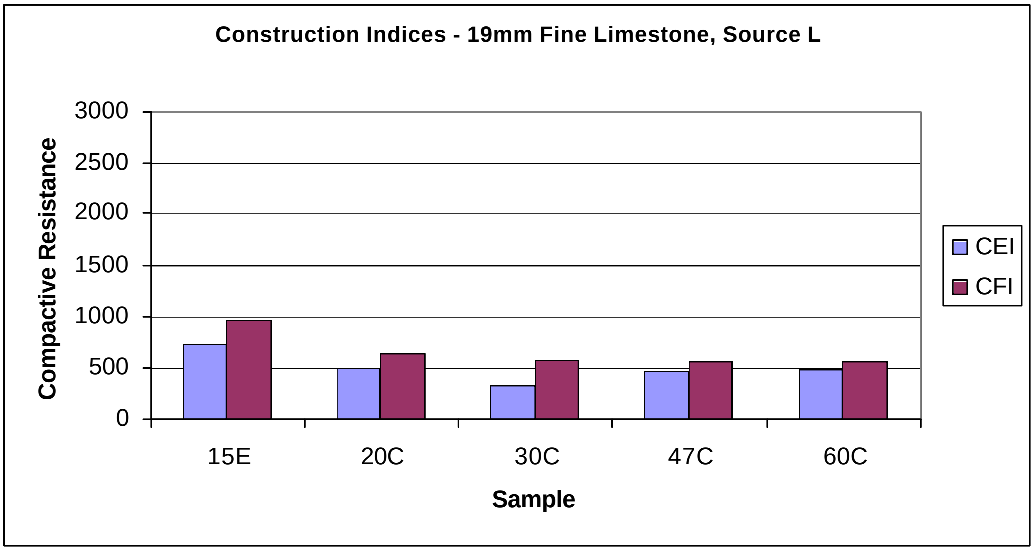
LABORATORY GLPA COMPACTIVE RESISTACNE FIGURES

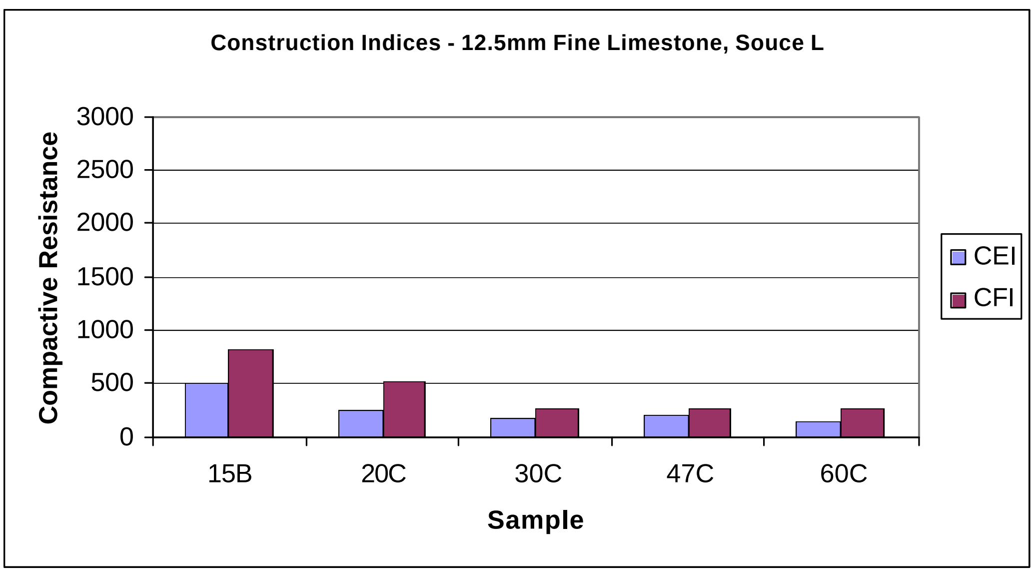
Source L Coarse



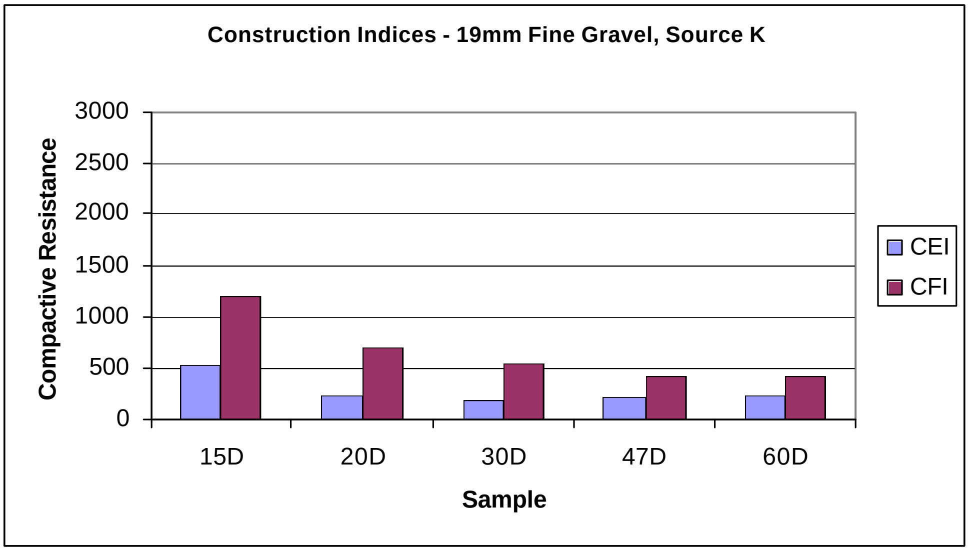


Source L Fine

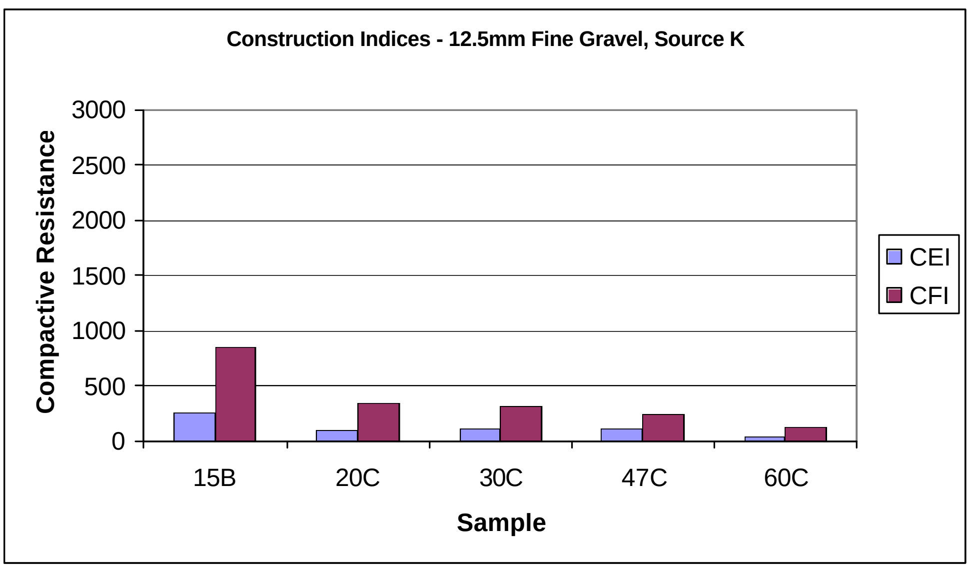




Source K

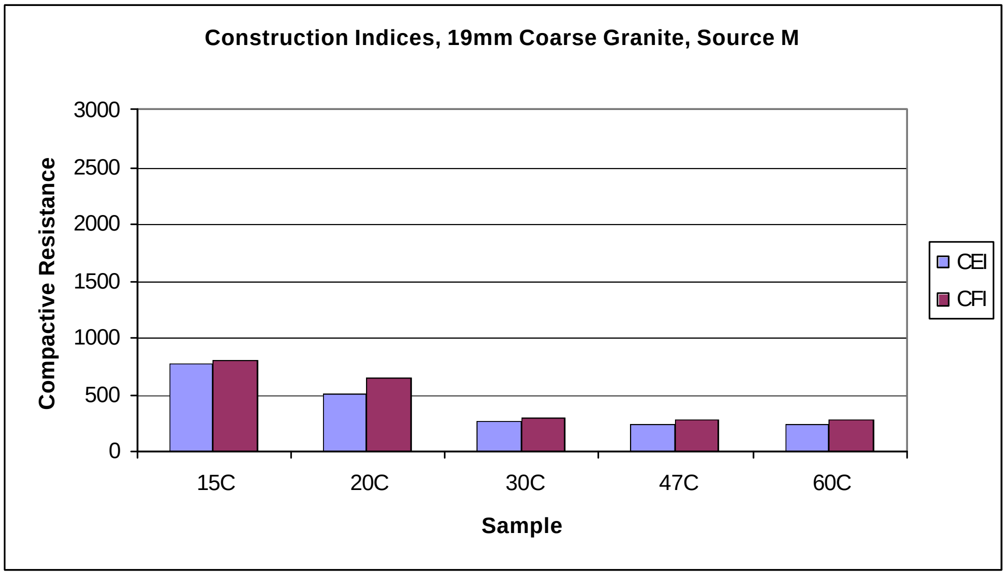


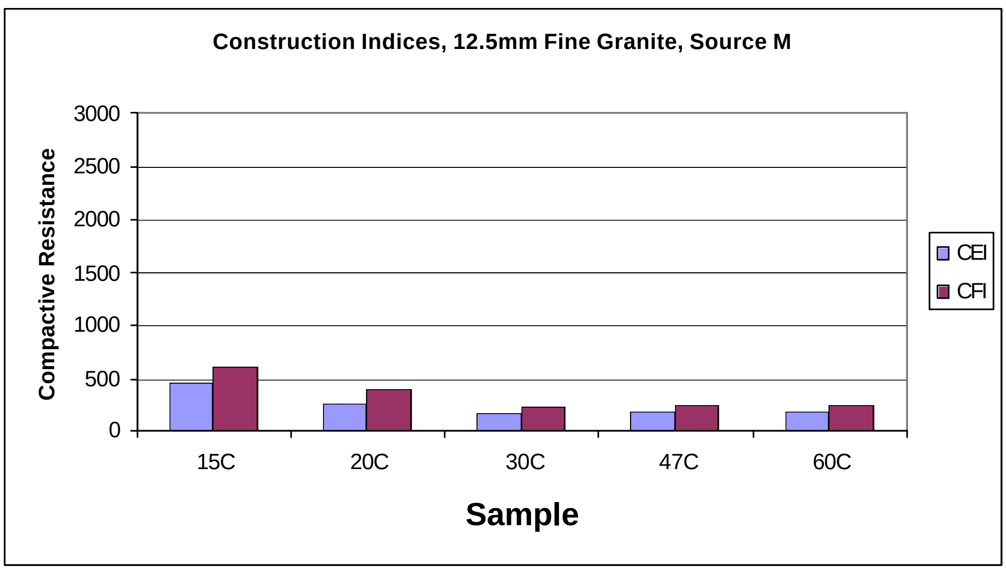
Construction Indices - 19mm Fine Gravel, Source K
Compactive Resistance
3000
2500
2000
1500
1000
500
0
15D
20D
30D
47D
60D
Sample
CEI
CFI



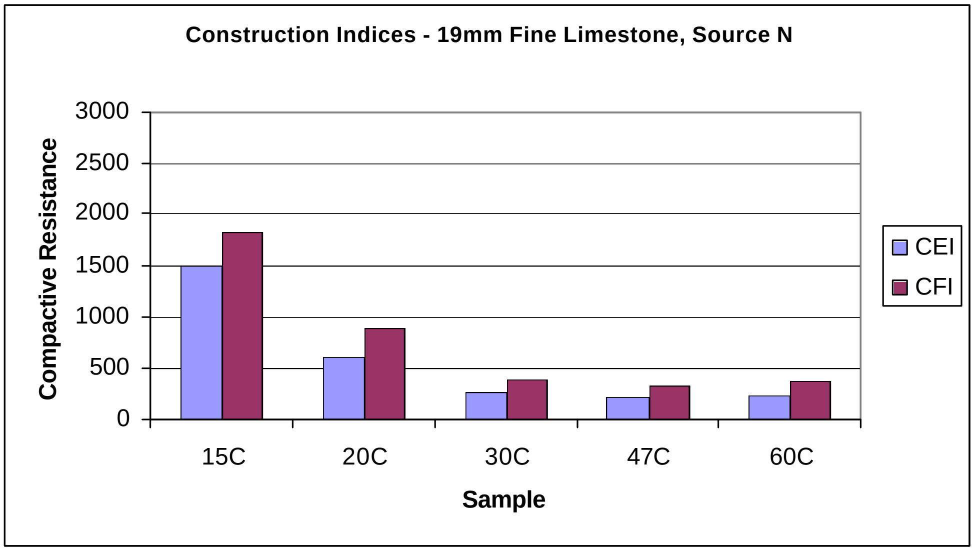
Construction Indices - 12.5mm Fine Gravel, Source K
Compactive Resistance
3000
2500
2000
1500
1000
500
0
15B
20C
30C
47C
60C
Sample
CEI
CFI

Source M

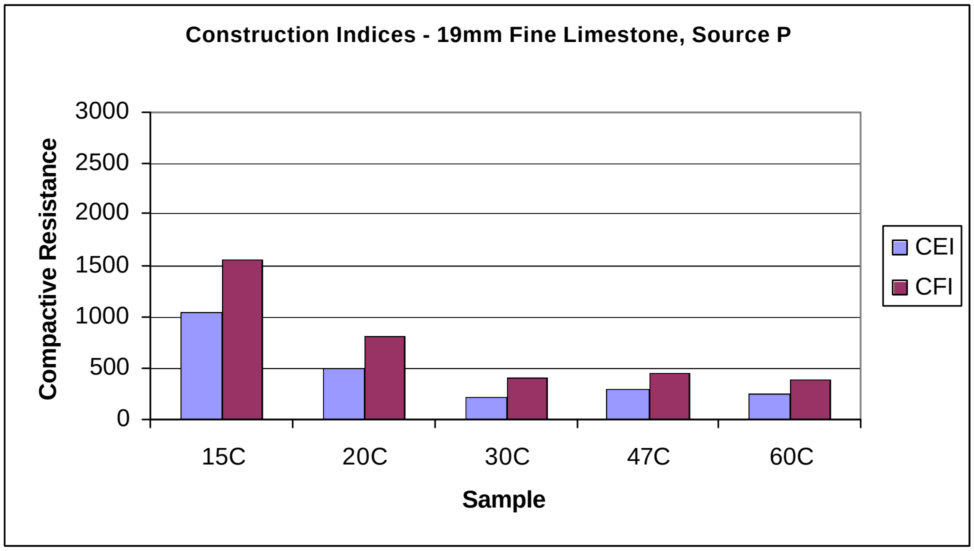

Construction Indices, 19mm Coarse Granite, Source M
Compactive Resistance
3000
2500
2000
1500
1000
500
0
15C
20C
30C
47C
60C
Sample
CEI
CFI


Construction Indices, 12.5mm Fine Granite, Source M
Compactive Resistance
3000
2500
2000
1500
1000
500
0
15C
20C
30C
47C
60C
Sample
CEI
CFI

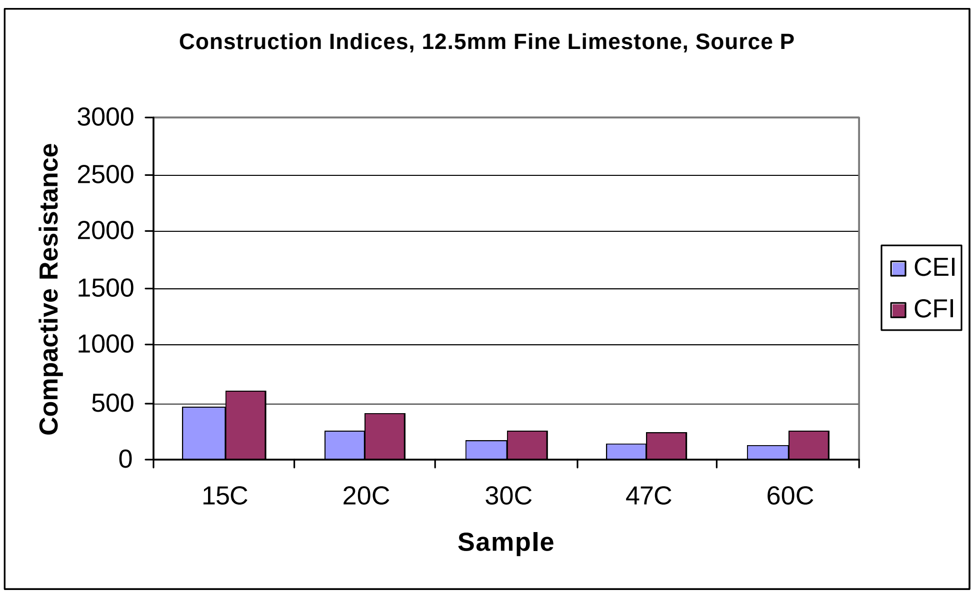
Source N


Construction Indices - 19mm Fine Limestone, Source N
Compactive Resistance
3000
2500
2000
1500
1000
500
0
15C
20C
30C
47C
60C
Sample
CEI
CFI

Source P



Construction Indices - 19mm Fine Limestone, Source P
Compactive Resistance
3000
2500
2000
1500
1000
500
0
15C
20C
30C
47C
60C
Sample
CEI
CFI



Construction Indices, 12.5mm Fine Limestone, Source P
Compactive Resistance
3000
2500
2000
1500
1000
500
0
15C
20C
30C
47C
60C
Sample
CEI
CFI

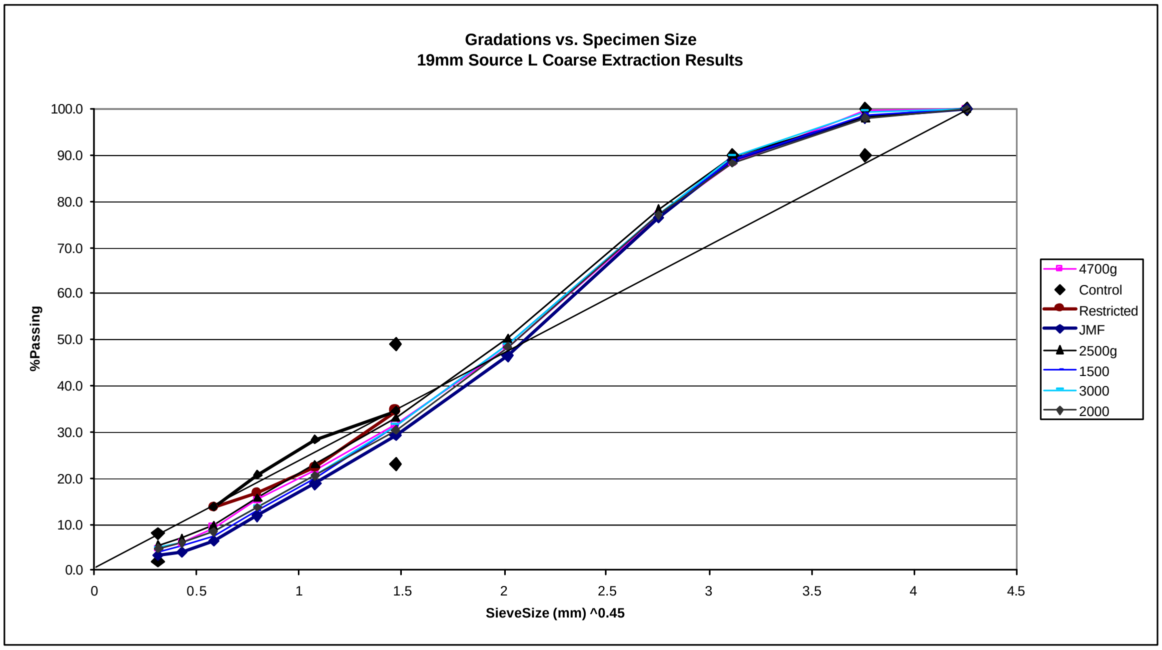
APPENDIX D

LABORATORY EXTRACTION RESULTS, GRADATION TABLES AND PLOTS

Source L Coarse, 19mm

19mm Coarse Limestone Extractions

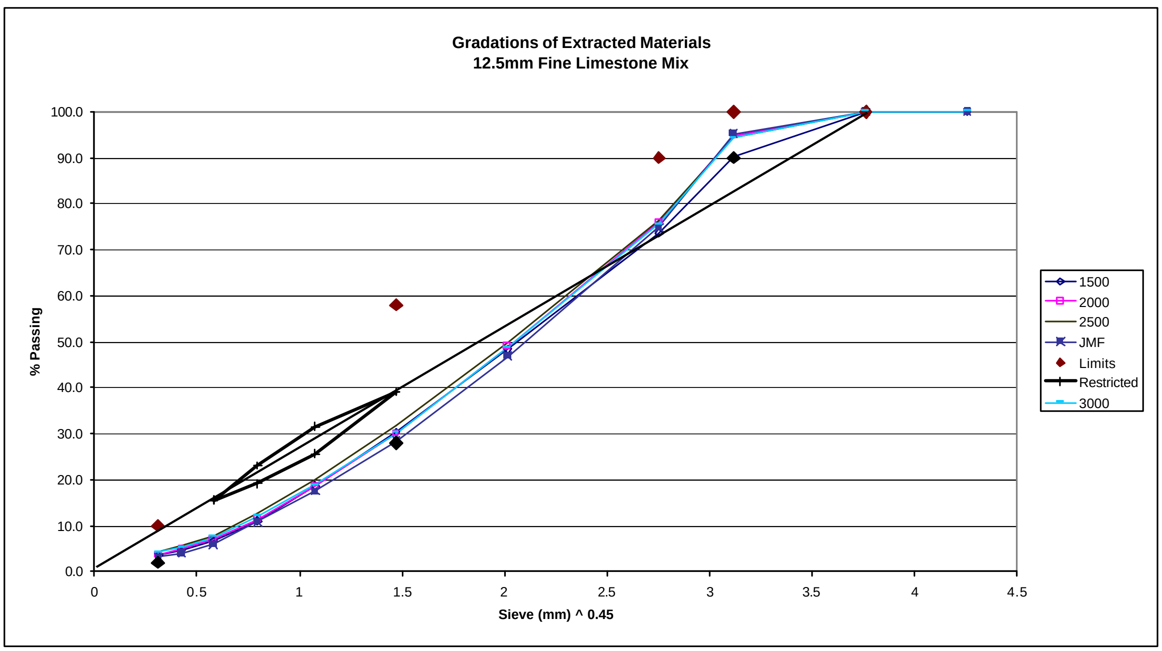
Specimen ID	19L15A	19L20A	19L25A	19L30B	19L47B	
Sieve	%Pass	%Pass	%Pass	%Pass	%Pass	**JMF**
25	100.0	100.0	100.0	100.0	100.0	**100**
19	98.7	98.1	98.1	99.4	99.5	**98.2**
12.5	88.8	88.3	89.8	89.7	88.2	**88.8**
9.5	77.0	77.1	78.3	77.0	76.8	**76.4**
4.75	49.0	48.5	50.3	49.0	48.4	**46.5**
2.36	31.2	30.3	33.0	31.4	31.6	**29.3**
1.18	19.9	20.5	23.0	20.4	21.8	**18.7**
0.6	12.8	13.6	15.7	13.7	15.3	**11.8**
0.3	7.5	8.3	9.7	8.4	9.3	**6.3**
0.15	5.2	5.9	6.9	6.0	5.9	**4**
0.075	4.0	4.7	5.4	4.8	4.6	**3.7**



Source L Coarse, 12.5mm

12.5mm Coarse Limestone Extractions

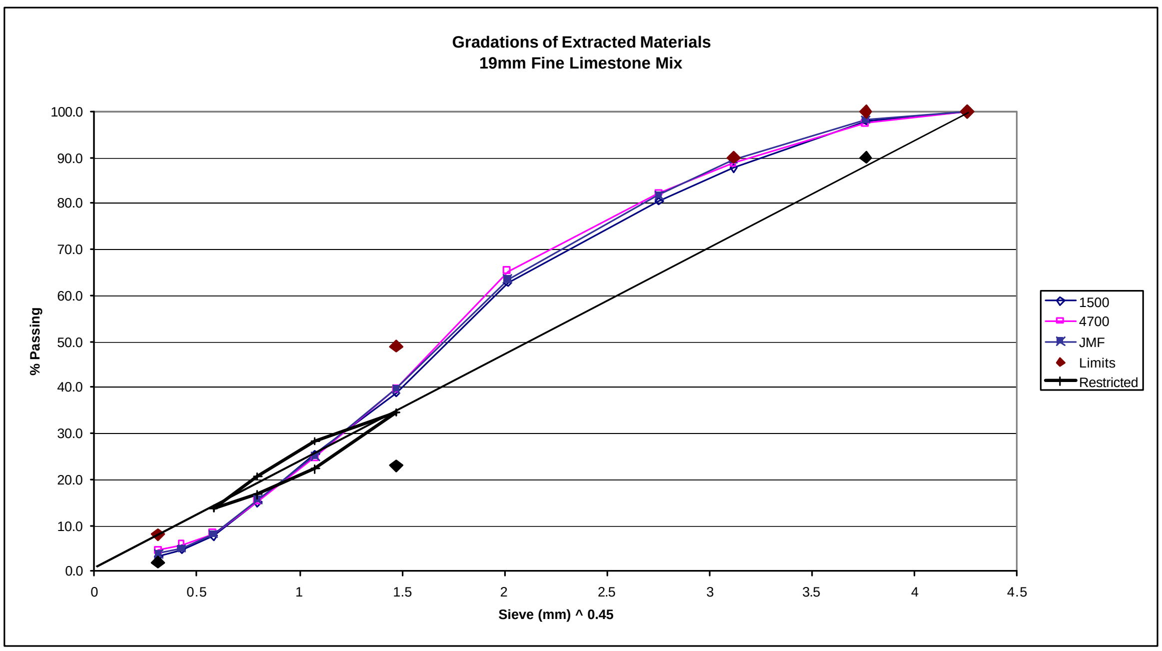
Specimen ID	125L15A	125L20B	125L25B	125L30B	125L47A	
Sieve	%Pass	%Pass	%Pass	%Pass	%Pass	**JMF**
25	100.0	100.0	100.0	100.0	100.0	**100**
19	100.0	100.0	100.0	100.0	100.0	**100**
12.5	90.1	94.8	94.3	94.3	94.1	**95.2**
9.5	73.6	76.0	76.2	75.6	75.5	**74.8**
4.75	48.3	49.0	49.9	48.7	49.2	**46.9**
2.36	30.3	30.1	31.8	30.1	30.4	**28.4**
1.18	18.7	18.5	19.9	18.8	18.3	**17.5**
0.6	11.0	11.4	12.6	12.0	11.5	**10.8**
0.3	6.7	7.0	7.8	7.5	7.6	**6**
0.15	4.7	4.9	5.7	5.3	5.7	**4**
0.075	3.6	3.7	4.4	4.1	4.5	**3.2**



Source L Fine, 19mm

19mm Fine Limestone Extractions

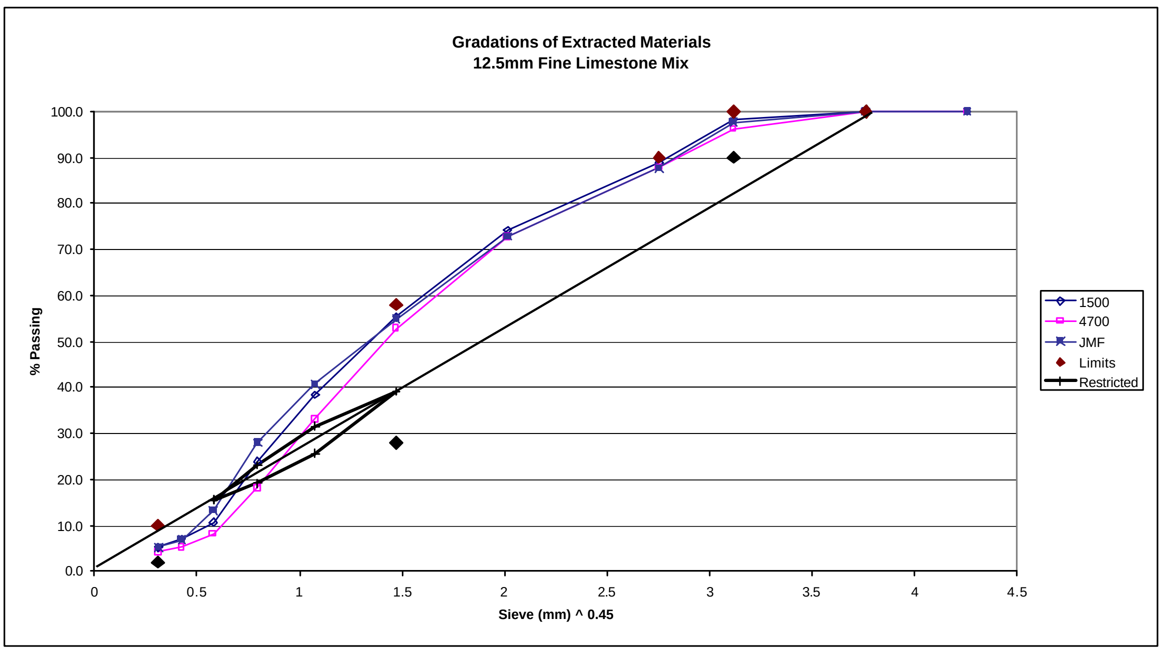
Specimen ID	19LF15A	19LF47B	
Sieve	%Pass	%Pass	**JMF**
25	100.0	100.0	**100**
19	98.0	97.4	**98.2**
12.5	87.7	88.7	**89.6**
9.5	80.4	82.3	**81.7**
4.75	62.8	65.3	**63.5**
2.36	38.8	39.7	**39.7**
1.18	25.6	24.8	**25.1**
0.6	15.0	15.2	**15.6**
0.3	7.7	8.3	**8.1**
0.15	4.8	5.7	**5**
0.075	3.3	4.5	**3.9**



Source L Fine, 12.5mm

12.5mm Fine Limestone Extractions

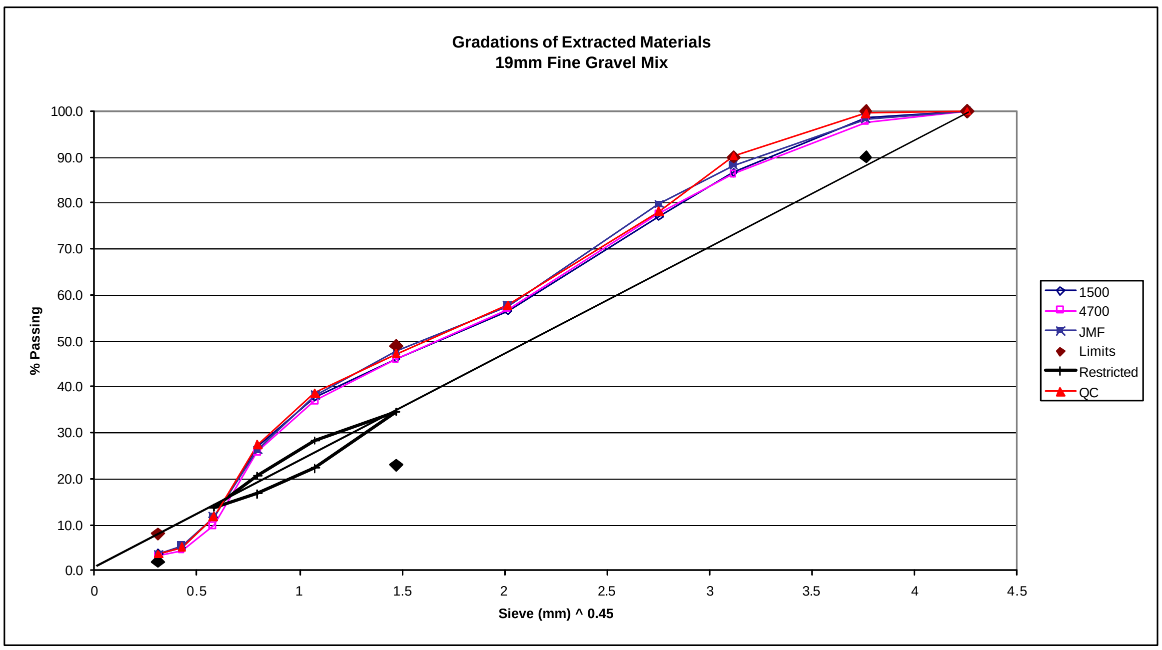
Specimen ID	125LF15A	125LF47E	
Sieve	%Pass	%Pass	**JMF**
25	100.0	100.0	**100**
19	100.0	100.0	**100**
12.5	98.2	96.2	**97.6**
9.5	89.0	87.8	**87.7**
4.75	74.2	72.7	**72.8**
2.36	55.3	52.8	**54.9**
1.18	38.4	33.0	**40.7**
0.6	24.0	18.1	**28**
0.3	10.7	8.1	**13.2**
0.15	7.1	5.3	**6.9**
0.075	5.3	4.3	**5.2**



Source K19mm

19mm Fine Gravel Extractions

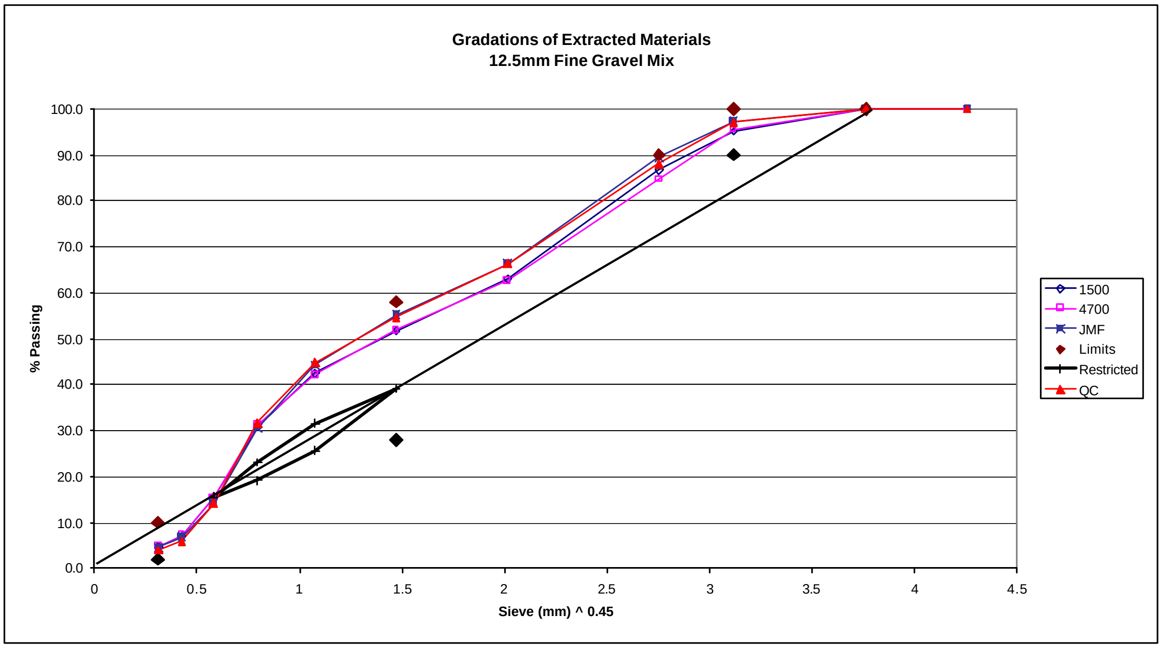
Specimen ID	19K15B	19K47D		
Sieve	%Pass	%Pass	**JMF**	**QC**
25	100.0	100.0	**100**	**100**
19	98.6	97.7	**98.4**	**99.5**
12.5	86.7	86.3	**88.3**	**90.2**
9.5	77.1	77.7	**79.8**	**78.1**
4.75	56.5	56.8	**57.6**	**57.8**
2.36	46.2	46.0	**47.9**	**47.2**
1.18	37.7	36.8	**38.2**	**38.7**
0.6	26.7	25.8	**26.2**	**27.4**
0.3	11.7	9.8	**11.8**	**11.7**
0.15	5.1	4.4	**5.4**	**5.1**
0.075	3.7	3.3	**3.6**	**3.6**



Source K 12.5mm

12.5mm Fine Gravel Extractions

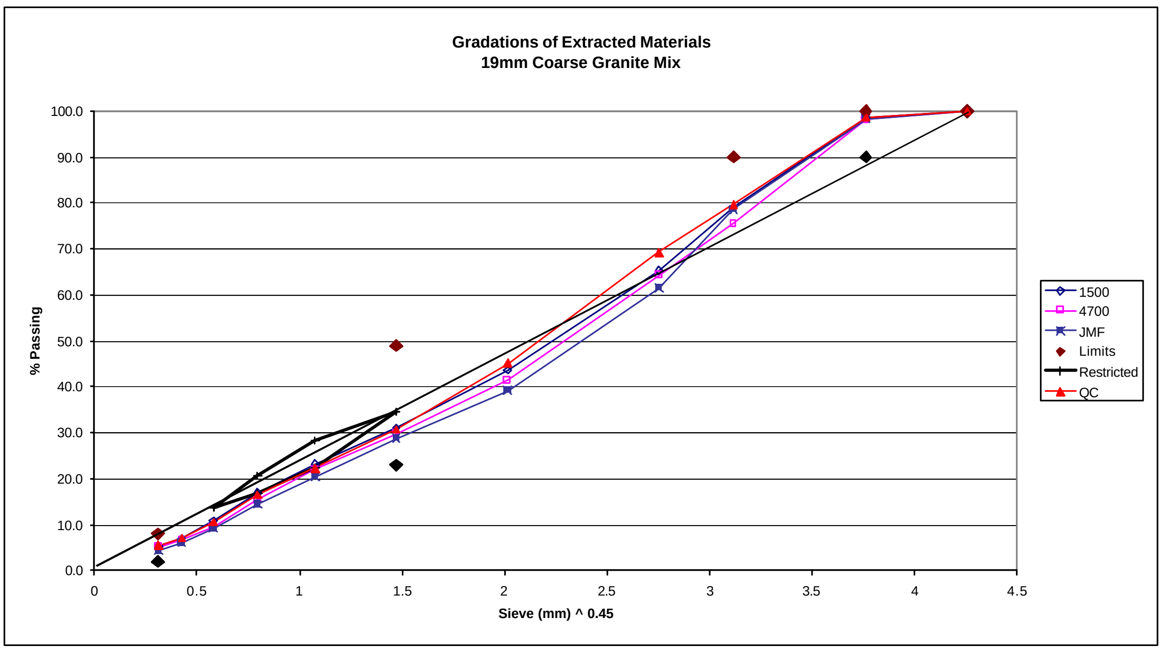
Specimen ID	125K15B	125K47B		
Sieve	%Pass	%Pass	JMF	QC
25	100.0	100.0	100	100
19	100.0	100.0	100	100
12.5	95.1	95.5	97.3	97.1
9.5	86.6	84.7	89.4	88
4.75	63.0	62.6	66.3	66.3
2.36	51.7	51.9	55.2	54.7
1.18	42.5	42.1	44.2	44.8
0.6	30.9	31.2	30.5	31.7
0.3	15.5	15.5	14.2	14.2
0.15	7.1	7.3	6.9	6
0.075	4.8	4.7	4.6	4



Source M 19mm

19mm Coarse Gravel Extractions

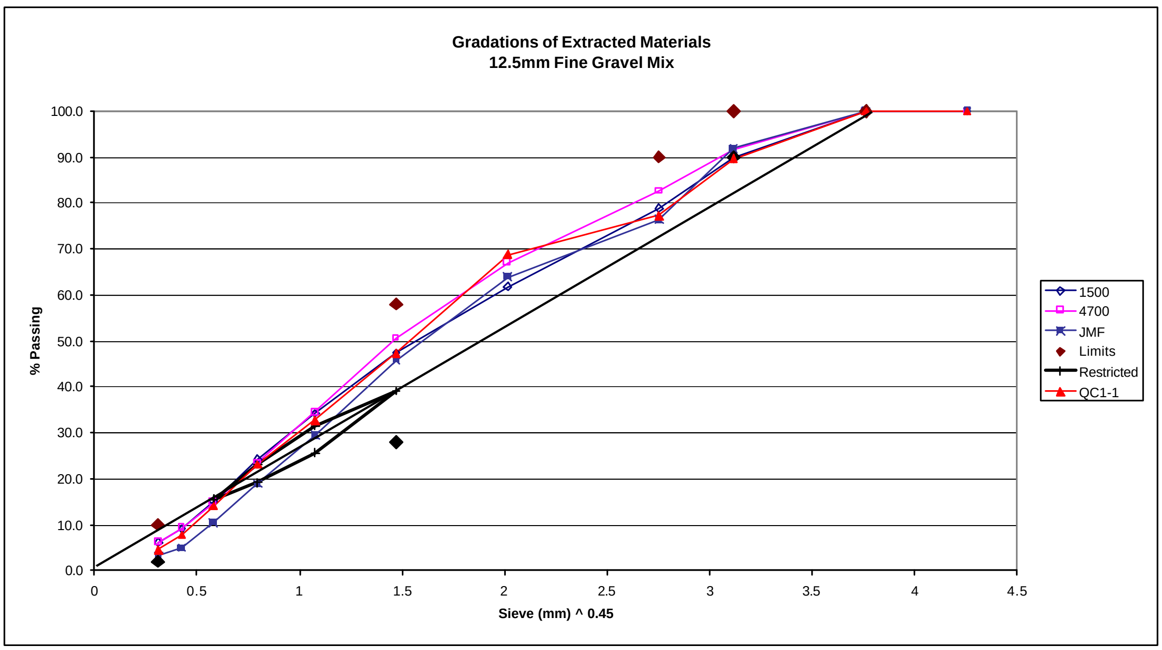
Specimen ID	19M15B	19M47B		
Sieve	%Pass	%Pass	**JMF**	**QC(1-1)**
25	100.0	100.0	**100**	**100**
19	98.5	98.1	**98.4**	**98.6**
12.5	79.1	75.6	**78.6**	**79.7**
9.5	65.3	64.3	**61.5**	**69.2**
4.75	43.6	41.4	**39.2**	**45.1**
2.36	31.0	29.8	**28.8**	**30.7**
1.18	23.2	22.1	**20.4**	**22.3**
0.6	17.0	15.3	**14.4**	**16.5**
0.3	10.8	9.5	**9.2**	**10.6**
0.15	6.9	6.7	**6.1**	**7.1**
0.075	5.3	5.2	**4.3**	**5.5**



Source M 12.5mm

12.5mm Fine Gravel Extractions

Specimen ID	125M15A	125M47A		
Sieve	%Pass	%Pass	JMF	QC (1-1)
25	100.0	100.0	100	100
19	100.0	100.0	100	100
12.5	89.8	91.6	91.9	89.6
9.5	78.9	82.6	76.4	77.2
4.75	61.8	67.0	63.9	68.8
2.36	47.3	50.5	45.8	47.4
1.18	34.2	34.4	29.4	32.8
0.6	24.2	23.5	18.9	23.1
0.3	15.2	14.9	10.5	14.1
0.15	9.1	9.2	5	7.8
0.075	6.2	6.1	3.2	4.5



APPENDIX E
FIELD STUDY TEMPERATURE ANALYSIS: TABLES

Field Study K, CTH "VV"

1.25" Surface

Roller	Temperature	Density	Roller	Temperature	Density	Roller	Temperature	Density
Screed	240	86.7	Screed	222	87.0	Screed	242	86.7
IR - 1.5	230	93.3	IR - 1	180	91.4	IR - 1	196	93.0
IR - 2	185	93.9	IR - 2	160	92.5	IR - 2	135	92.8
IR - 3	155	93.7	IR - 3	141	93.3	IR - 3	130	94.1
IR - 4	150	93.7	IR - 4	142	93.5			
CR - 1			CR - 1			CR - 1	116	94.1
CR - 2			CR - 2			CR - 2	112	95.3
CR - 3			CR - 3					
Final	100	94.8	CR - 4	111	93.4			

1.75" Surface

Roller	Temperature	Density	Roller	Temperature	Density	Roller	Temperature	Density
Screed	231	85.0	Screed	245	84.0	Screed	270	85.1
IR - 1	193	90.3	IR - 1	233	89.7	IR - 1	220	90.6
IR - 2	170	92.1	IR - 2	200	92.2	IR - 2	140	91.7
IR - 3	132	93.4	IR - 3	200	92.7	IR - 3	110	91.9
IR - 4	112	92.1	IR - 4	180	93.0			
			IR - 5	160	94.8			
			IR - 6	160	94.7			
CR - 1	100	94.8	CR - 1	130	94.2	CR - 1	114	93.9
			CR - 2			CR - 2		
			CR - 3	122	94.2	Final	98	92.7

2.25" Surface

Roller	Temperature	Density	Roller	Temperature	Density	Roller	Temperature	Density
Screed	245	85.5	Screed	243	83.8	Screed	260	86.2
IR - 1	200	90.1	IR - 1	228	91.4	IR - 1	230	90.4
IR - 2	172	90.9	IR - 2	200	94.9	IR - 2	200	93.5
IR - 3	150	92.3	IR - 3	170	93.2	IR - 3	170	94.0
IR - 4			IR - 4	150	93.5	IR - 4	153	93.9
IR - 5	115	93.5						
CR - 1	110	93.6	CR - 1			CR - 1	119	92.9
CR - 2	93	93.7	CR - 2	125	93.4	CR - 2	115	93.7
			CR - 3			CR - 3	113	
			CR - 4			CR - 4		
			CR - 5	116	94.4	CR - 5		
						Final	102	96.0

Field Study M, STH 13

1.75" Binder

Roller	Temperature	Density	Roller	Temperature	Density
Screed	250	75.8	Screed	250	75.7
TR - 1			TR - 1		
TR - 2			TR - 2		
TR - 3			TR - 3		
TR - 4	210	85.4	TR - 4		
			TR - 5		
			TR - 6	200	85.9
VR - 1	175	88.2	VR - 1	165	89.4
VR - 2	160	90	VR - 2	160	89.8
CR -1	120	90.9	CR -1	120	90.4
CR -2	110	90.7	CR -2	110	90.8

2.00" Binder

Roller	Temperature	Density	Roller	Temperature	Density
Screed	260	72.7	Screed	270	74.9
TR - 1			TR - 1		
TR - 2			TR - 2		
TR - 3			TR - 3		
TR - 4	230	83.5	TR - 4	230	84.3
			TR - 5		
			TR - 6		
			TR - 7		
			TR - 8	200	84.9
VR - 1	185	87.5	VR - 1	180	89
VR - 2	175	88.5	VR - 2	170	89.3
CR -1			CR -1		
CR -2			CR -2		
CR -3	115	89.3	CR -3	115	90.7

2.25" Binder

Roller	Temperature	Density	Roller	Temperature	Density
Screed	255	73.5	Screed	260	74.3
TR - 1			TR - 1		
TR - 2			TR - 2		
TR - 3			TR - 3		
TR - 4			TR - 4		
TR - 5			TR - 5	240	83.7
TR - 6			TR - 6		
TR - 7	220	85.9			
VR - 1	180	88	VR - 1	210	86.8
VR - 2	172	89.2	VR - 2	200	87.6
			VR - 3	190	88.6
			VR - 4		
CR -1	140	90.4	CR -1		
CR -2	115	91.8	CR -2		
			CR -3		
			CR -4	135	91
			CR -5	110	91.3

2.50" Binder

Roller	Temperature	Density	Roller	Temperature	Density
Screed	265	73.4	Screed	245	73.3
TR - 1			TR - 1		
TR - 2			TR - 2		
TR - 3			TR - 3		
TR - 4	225	79.7	TR - 4		
TR - 5			TR - 5		
TR - 6			TR - 6		
			TR - 7	240	84.6
			TR - 8		
			TR - 9		
			TR - 10		
			TR - 11		
			TR - 12		
			TR - 13	225	85.3
			TR - 14		
VR - 1	205	89.7	VR - 1	200	89.9
VR - 2	182	88.4	VR - 2	195	88.6
			VR - 3		
			VR - 4		
			VR - 5		
			VR - 6	155	91.4
CR -1	135	90.3	CR -1	140	92

APPENDIX F

FIELD STUDY DENSITY TABLES

Field Study K

19mm Gravel Binder

Lift Thickness (Ratio)	Screed	2-Vib + 2Rub Tire	Final
1.5"	83.8	91.7	93.1
1.5"	81.4	92.4	93.5
1.5"	82.4	91.2	90.8
Average 1.5" (2)	**82.5**	**91.8**	**92.5**
2.0"	78.6	88.1	88.1
2.0"	81.7	91.7	92.5
2.0"	80.6	93.3	94.1
Average 2.0" (2.66)	**80.3**	**91.0**	**91.6**
3.5"	77.6	92.5	96.4
3.5"	83.5	91.8	92.5
3.5"	79.9	91.5	93.6
Average 3.5" (4.66)	**80.3**	**91.9**	**94.2**
4.5"	80.4	90.6	95.9
4.5"	81.4	90.1	93.2
4.5"	82.4	91.8	95
Average 4.5" (6)	**81.4**	**90.8**	**94.7**

12.5mm Gravel Surface

Lift Thickness (Ratio)	Screed	4-Vibratory	Final
1.25"	86.7	93.7	94.8
1.25"	87.0	93.5	93.4
1.25"	86.7	94.1	95.3
Average 1.25" (2.5)	**86.8**	**93.8**	**94.5**
1.75"	85.0	92.1	94.8
1.75"	84.0	93.0	94.2
1.75"	85.1	91.9	92.7
Average 1.75" (3.5)	**84.7**	**92.3**	**93.9**
2.25"	85.5	93.5	93.7
2.25"	83.8	93.5	94.4
2.25"	86.2	93.9	96.0
Average 2.25" (4.5)	**85.2**	**93.6**	**94.7**
3.0"	84.4	88.1	89.5
3.0"	84.6	92.3	92.3
3.0"	80.5	91.4	91.8
Average 3.0" (6)	**83.2**	**90.6**	**91.2**

Field Study M

19mm Granite Binder

Test	Thickness (Ratio)	Screed	Tire Rolling	Vibratory Rolling	Cold Rolling
1.75-1	1.75" (2.3)	75	85.1	88.1	89
1.75-2	1.75" (2.3)	75.8	85.4	90	90.7
1.75-3	1.75" (2.3)	74.1		88.1	90.6
1.75-4	1.75" (2.3)	75.7	85.9	90.8	90.6
1.75-Average	**1.75" (2.3)**	**75.2**	**85.7**	**89.6**	**90.6**
2.0-1	2" (2.7)	74.4	84.5	88	88
2.0-2	2" (2.7)	74.9	84.9	89.3	90.7
2.0-4	2" (2.7)	72.7	83.5	88.5	89.3
2.0-Average	**2.0" (2.7)**	**74.0**	**84.3**	**88.6**	**89.3**
2.25-1	2.25" (3)	74.3	83.7	88.6	91.3
2.25-2	2.25" (3)	73.5	85.9	90.4	91.8
2.25-3	2.25" (3)	72.1	83.4	89.4	92.6
2.25-4	2.25" (3)	74	82.3	88.9	90.7
2.25-Average	**2.25" (3.0)**	**73.2**	**83.9**	**89.6**	**91.7**
2.5-1	2.5" (3.3)	73.3	85.3	88.6	92
2.5-2	2.5" (3.3)	73.9	84.1	89.8	91.4
2.5-3	2.5" (3.3)	73.4	86.7	88.4	90.3
2.5-Average	**3" (3.3)**	**73.5**	**85.4**	**88.9**	**91.2**

12.5mm Granite Surface

Test	Thickness (Ratio)	Screed	Tire Rolling	Vibratory Rolling	Cold Rolling
1.5-1	1.5" (3)	80	86	86.3	91.7
1.5-2	1.5" (3)	80.4	84.3	89.8	93.4
1.5-Average	**1.5" (3)**	**80.2**	**85.2**	**88.1**	**92.6**
1.75-1	1.75" (3.5)	79.1	88.3	90.1	
1.75-2	1.75" (3.5)	77.4	86.8	91.6	
1.75-3	1.75" (3.5)	71.6	86.5	91.8	92.4
1.75-Average	**1.75" (3.5)**	**76.0**	**87.2**	**91.2**	**92.4**
2.0-1	2" (4)	77.4	85.1	92	92.5
2.0-2	2" (4)	76.9	88.2	91.8	92.7
2.0-3	2" (4)	78.4	87.8	90.7	
2.0-Average	**2.0" (4)**	**77.6**	**87.0**	**91.5**	**92.6**
2.25-1	2.25" (4.5)	78.2	86.8	91	94.4
2.25-2	2.25" (4.5)	78.3	84.5	91	92.2
2.25 Average	**2.25" (4.5)**	**78.3**	**85.7**	**91.0**	**93.3**

Field Study N

19mm Limestone Binder

Test	Thickness (Ratio)	Screed	Vibratory Rolling	Tire Rolling	Cold Rolling
1.5-1	1.5" (2.0)	80.2	90.3	90.3	92.4
1.5-2	1.5" (2.0)	76	90	90.8	92.5
1.5-Average	**1.5" (2.0)**	**78.1**	**90.2**	**90.6**	**92.5**
2.0-1	2" (2.7)	77.9	90.2	91.8	92.7
2.0-2	2" (2.7)		90.2	92.1	93.2
2.0-3	2" (2.7)	80	90.5	92.7	91.2
2.0-Average	**2" (2.7)**	**79.0**	**90.3**	**92.2**	**92.4**
2.25-1	2.25" (3)	77.7	88.9	90.9	92
2.25-2	2.25" (3)	78.1	89.4	90.6	92.1
2.25-Average	**2.25" (3)**	**77.9**	**89.2**	**90.8**	**92.1**
2.5-1	2.5" (3.3)	75.7	90.1	90.3	93.2
2.5-2	2.5" (3.3)	79.4	91.2	92.5	94.8
2.5-3	2.5" (3.3)	77.5	89.8	89.3	95.5
2.5-4	2.5" (3.3)		90.6	93.2	93.9
2.5-Average	**2.5" (3.3)**	**77.5**	**90.4**	**91.3**	**94.4**

Field Study P

19mm Limestone Binder

Test	Thickness (Ratio)	Screed	Vibratory Roller	Cold Roller
2.5-1	2.5" (3.3)	79.3	92.5	93.9
2.5-2	2.5" (3.3)	82.1	90.1	92.4
2.5-3	2.5" (3.3)	77.2	90.6	91.7
2.5-4	2.5" (3.3)	78.7	90.7	91.8
2.5 Average	**2.5" (3.3)**	**79.3**	**91.0**	**92.5**
3.0-1	3" (4.0)	79.5	90.9	92.6
3.0-2	3" (4.0)	78.6	91.9	91.7
3.0-3	3" (4.0)	79.6	91.3	93.8
3.0-4	3" (4.0)	81.3	92.2	94.4
3.0 Average	**3" (4.0)**	**79.8**	**91.6**	**93.1**
3.25-1	3.25" (4.3)	78.7	91.6	92.5
3.25-2	3.25" (4.3)	78.5	92.1	94.3
3.25-3	3.25" (4.3)	78.9	90.5	91.4
3.25 Average	**3.25" (4.3)**	**78.7**	**91.4**	**92.7**

12.5mm Limestone Surface

Test	Thickness (Ratio)	Screed	Vibratory Roller	Cold Roller
1.25-1	1.25" (2.5)	78.2	89.7	91.6
1.25-2	1.25" (2.5)	78.7	91.7	92
1.25-3	1.25" (2.5)	80.2	91.2	91.3
1.25-4	1.25" (2.5)	79.8	89.7	91.3
1.25 Average	**1.25" (2.5)**	**79.2**	**90.6**	**91.6**
1.5-1	1.5" (3.0)	80.3	91.2	91.9
1.5-2	1.5" (3.0)	79.9	90.2	91.9
1.5-3	1.5" (3.0)	78.8	89.9	91.2
1.5-4	1.5" (3.0)	78	89	90.9
1.5 Average	**1.5" (3.0)**	**79.3**	**90.1**	**91.5**
2.0-1	2.0" (4.0)	80.1	93	93.9
2.0-2	2.0" (4.0)	79.3	92.2	93.4
2.0-3	2.0" (4.0)	78.5	90.3	92
2.0-4	2.0" (4.0)	77.6	92	92.7
2.0 Average	**2.0" (4.0)**	**78.9**	**91.9**	**93.0**